XI. Bakerian Lecture.—*The Crystalline Structure of Metals.*

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[Plates 15–28.]

The microscopic study of metals was initiated by Sorby,* and has been pursued by Arnold, Andrews, Behrens, Charpy, Chernoff, Howe, Martens, Osmond, Roberts-Austen, Sauveur, Stead, Wedding, Werth and others.† The work of these authors has demonstrated the value of the microscope in metallurgy, not only as an aid to analysis, but as a means of observing structure. The structure of pure metals, of metals containing small quantities of foreign matter, and of alloys, has been made the subject of microscopic examination, and important conclusions have been reached. The work to be described in this paper proceeds on the same general lines. A large part of it deals with a branch of the subject which has not hitherto received much notice, namely, the effects of strain. The writers believe that they have established the fact that the structure of metals is crystalline even under conditions which might be supposed to destroy crystalline structure. They have found that the plastic yielding of metals when severely strained occurs in such a manner that the crystalline structure is preserved. The observations to be described show how crystalline aggregates exhibit plasticity, and how, after straining, a metal continues to be a crystalline aggregate. The distinction which is often drawn between crystalline and non-crystalline states in metals appears to be unfounded.

Except for a few simple innovations, the methods of experiment used in this research, especially as regards the preparation of specimens, do not differ materially from those of earlier workers. The specimens were first polished on commercial emery-paper which had been previously rubbed on a piece of hard steel in order to remove the coarser particles. They were finished on a rapidly revolving disc coated with fine wash-leather and charged with a thin paste of rouge and water. For most purposes

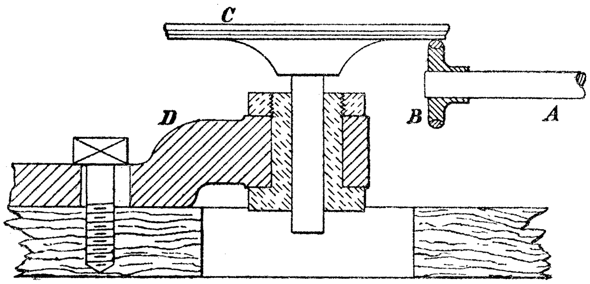
* 'Roy. Soc. Proc.,' vol. 13, p. 333.

† For the bibliography see Sir W. Roberts-Austen's book on 'Metallurgy' (Edition of 1895); also a paper by Mr. J. E. Stead on the "Crystalline Structure of Iron and Steel," 'Journal of the Iron and Steel Institute,' 1898.

the finest jeweller's rouge is suitable, but in special cases we resorted to the use of peroxide of iron obtained by precipitation from a solution of pure ferric chloride.

The polishing machine is shown in diagram-section in fig. 1. *A* is the spindle ot an electro-motor carrying a small driving disc *B*, fitted with a rubber ring to increase the driving friction. The polishing disc *C* is horizontal and has a vertical axis running in a bearing in the casting *D*. The under side of the polishing disc bears upon the driving wheel *B* and takes motion from it. When it is desired to stop temporarily the polishing disc is raised out of contact with the driving wheel. The

Fig. 1.



casting *D* is held to the base-board by a bolt passing through a slot which allows the disc to be brought nearer to the motor, so that it may bear upon the driving wheel at any desired distance from its axis, thus giving a means of varying the speed. More usually, however, the speed was varied by regulating the current in the motor.

With metals which are very liable to tarnish, wet polishing has to be avoided; in some cases dry rouge, and in others rouge moistened with a little paraffin, may be used—the latter we found particularly useful in polishing copper. But in some metals, especially the more fusible ones, such as lead, zinc, and tin, it is difficult to obtain a satisfactory surface by any method of polishing. In most of these cases, however, a method of obtaining a good surface entirely without polishing becomes available. This consists in pouring the molten metal on a smooth body, such as glass or polished steel, in contact with which it is allowed to solidify. We have, as a rule, used glass for this purpose, and in spite of frequent failures, due to fracture of the glass or to less obvious causes, we find that it is generally practicable to get a good specimen in this way with much less trouble than is required to produce a specimen of iron or steel by the ordinary process of polishing. This method of "glass casting" cannot well be applied to metals which oxidize at temperatures below their melting points, and for metals which have a very high melting point a smooth body other than glass must be used. The metals most readily treated by casting against a smooth surface are gold, bismuth, cadmium, lead, tin, zinc, and fusible alloys.

In the examination of lead another method of obtaining a good surface, without either melting or polishing, was also used. A face of the specimen was freshly cut to remove the tarnish, and was then pressed against a smooth surface of plate-glass. Whenever a sufficient pressure could be reached without breaking the glass a very

beautiful surface was obtained. In some cases polished steel was used as the smooth object against which the metal was pressed.

The polished surfaces were, in general, slightly etched before microscopic examination, in most instances by dilute nitric acid. Frequently, however, no etching was resorted to, especially in observations dealing with the effects of strain. It has been pointed out by CHARPY that straining, by the relative displacement which it brings about among the crystalline grains, serves to reveal the structure. Our observations confirm this, and in some cases we found that a better investigation of the effects of strain could be made when the surface was not etched.

Most of the microscopic observations were made with ZEISS' apochromatic lenses, a 2-millim. homogeneous immersion lens of 1·40 aperture being employed for high power work, with compensating eye-pieces magnifying from 4 to 18 times, giving in direct vision a total magnification up to 3000 diameters. "Vertical" illumination was generally used, the objective serving as condenser, but in some cases the specimens were examined under oblique light. Photographic records of the most interesting features were obtained, some of which are reproduced in this paper. The source of light was an arc lamp, the beam from which was condensed on the illuminator through a "Gifford" screen which allowed only a very limited portion of the spectrum to pass. Most of the high power photographs were taken with a magnification of 1000 diameters; in a few instances it was 4000 diameters or more.

It is well known that when the polished surface of a metal, such as gold or iron, is lightly etched, and is then examined by means of normally reflected ("vertical") light, the surface appears divided up into a number of areas separated by more or less polygonal boundaries. These areas are the sections of the crystalline grains which constitute the mass of the metal; the boundaries between them have been made evident by the differential action of the acid which has produced differences of level by attacking one grain more energetically than its neighbour. Fig. 2 (Plate 15) illustrates this appearance in ordinary iron. There the black patches are due to the presence of slag, and the black lines forming the boundaries are due to differences of level between the grains. Each of the short sloping surfaces which connects one grain with another appears black because it does not reflect the normally incident light back into the tube.

It is also well known that a further differential action of the acid is to reveal a difference of texture between the grains. This is visible in fig. 2, but is much more pronounced when the surface is examined under oblique light. When the light is uni-directional or nearly so, the various grains differ very much in brightness and colour—some are almost black, while others shine out brightly; if, however, the incidence of the light or the orientation of the specimen be changed, other grains shine out strongly, while those previously bright become dark. This effect was first observed in gold by ARNOLD ('Engineering,' February 7, 1896), who accounted for it by considering that each crystalline grain is built up of a very large number of what

he (following ANDREWS) calls secondary crystals, which have different orientations in different grains. Substantially the same view is expressed in other terms by OSMOND and ROBERTS-AUSTEN ('Phil. Trans.,' A, vol. 187, pp. 424–5), who speak of little crystals, "the general orientation of which remains constant in the area of each grain." Many beautiful illustrations of the same effect in iron have been given by STEAD, along with a clear discussion of the cause to which this appearance is to be ascribed ('Journal of the Iron and Steel Institute,' 1898). A striking instance is shown in his photographs of steel containing about $4\frac{1}{2}$ per cent. of silicon. The fractured ingot of this material exhibits large crystals, and by deeply etching a polished surface he has obtained a fine development of the regularly oriented elements of which the crystalline grains are built up, on a scale so large as to be clear with little or no magnification.

These observations have made it plain that each of the grains which appear on the polished and etched surface of a metal is simply a crystal, the growth of which has been arrested by its meeting with neighbouring grains. The irregular boundaries of the grains are determined by these meetings. We may imagine the grains to grow from as many centres or nuclei as there are grains. Each grain is built up of similarly oriented parts, but the orientation changes from grain to grain. Etching a polished surface develops a multitude of facets which have the same orientation over the surface of any one grain, but different orientations in different grains. Seen under oblique illumination these facets show themselves to be similarly oriented in each grain by the uniform manner in which the grain reflects light, and by the disappearance of brightness over the whole surface of the grain when the incidence of the light is changed. The mass of the grain consists of similarly oriented elements; as to the size of the elements no assumption need be made. The facets which are developed by etching do not, in general, appear of constant size; it is to the constancy of their orientation that the effect is due.

A striking illustration of how a metal crystallises by the simultaneous building up of groups of elements from a number of centres, the elements in each group being similarly oriented, while the orientation varies from group to group, may be seen in a cake of solidifying bismuth from which the still molten metal has been poured away. The operation then goes on upon a scale so large that no magnification is required to make it apparent. Fig. 3 is a photograph of a specimen of bismuth in the Cambridge University Museum of Mineralogy, for the loan of which the authors are indebted to Professor LEWIS and Mr. A. HUTCHINSON. The scale of the photograph is only about two-fifths natural size, but it shows well how the cake is made up of crystalline grains, each composed of elements with a definite orientation, the boundaries between the grains being due to the casual meeting of the several groups in the process of growth.

The references given above will show that there is nothing novel in this view of the structure of metals. Several of the authors' observations may, however, be

mentioned as affording additional evidence that the structure of metals in general consists of crystalline grains built up in the manner which has been described. One class of evidence has been obtained by an examination of specimens of iron which had been deeply etched under very high magnification, *i.e.*, 2000 to 3000 diameters. Under favourable circumstances it is possible to resolve the minute structure to which the peculiar reflection of oblique light is due. The face of each grain is then seen to be covered with minute projections resembling scales, more or less square or oblong in shape and similar and similarly oriented over the entire face of one grain. Fig. 4 is a photograph of this appearance as seen in nearly pure wrought iron: it may be compared (as Mr. STEAD compares a like appearance occurring on a large scale in silicon steel) to the arrangement of slates on the roof of a house. In other cases the action of the acid is different; the general surface of a grain cannot be resolved under the highest powers, but here and there the acid has etched out minute pits showing a distinct geometric form. All these pits found over the face of one grain are similar and similarly situated figures, but the shape and orientation of the pits changes as soon as a boundary is crossed. This is shown in a very striking way where a comparatively large pit crosses the boundary so that a portion appears on each side. Each portion preserves its proper shape and orientation, and there is consequently a marked angle in the sides of the pit where the sides cross the boundary. The shape of all these pits in iron is consistent with the assumption that they are plane sections of cubes or octahedra.

Fig. 5 (Plate 16) is a photograph of such etched pits in Swedish iron.

A good development of geometrically etched pits is not very readily obtained: in some specimens of iron they occur with much greater readiness than in others, and this occurrence is to some extent an accident of etching. Possibly the presence of a minute quantity of impurity in the iron is an essential factor, but we have no evidence on the subject. Geometrical etched pits are a well known phenomenon in non-metallic mineral crystals. BAUMHAUER* finds that they have a definite relation to the crystallographic nature of the crystal upon which they occur—but the facets developed by etching often lie in planes which are not parallel to the natural faces of the crystal. He finds that these etched pits, though generally truly geometrical, frequently show curved or irregular outlines which he attributes to local concentration of the acid. We find that curved or irregular outlines often occur in the larger etched pits in iron, and in view of BAUMHAUER's observations it is clear that they cannot be taken to affect the evidence for the strictly crystalline nature of the metal, since similar appearances are to be found in bodies that are characteristically crystalline.

When metals are cast against glass or other smooth bodies, to get a surface fit for microscopic examination, evidences of crystalline structure appear apart from any-

* BAUMHAUER, 'Resultate der Aetzmethode in der Krystallographischen Forschung.' WILHELM ENGELMANN, Leipzig, 1894.

thing that is shown by etching. The cast surface generally shows clearly, without any etching, the boundaries between the crystalline grains. Good examples of this are found in cadmium, lead, tin, and zinc. In some instances the boundaries between the grains are emphasised in a remarkable way by the accumulation there of air or of gas given off by the metal during solidification. The boundaries then appear as more or less deep and wide channels. As the growth of the crystalline grains proceeds most of the air or gas which has been entrapped between the glass and the metal, and most of the gas given out from solution in the metal itself, tends to accumulate at the boundaries, which are the last parts of the surface to undergo solidification. A network of channels consequently appears on the surface next the glass; in general these channels coincide with boundaries, but occasionally a channel forms a *cul-de-sac* or terminates in a large cavity which is obviously a bubble or blow-hole. Fig. 6 shows the appearance of a surface of cadmium cast against glass under conditions of temperature favourable to the formation of these channels. By etching or straining the specimen it is easy to prove that each channel (except when it is a *cul-de-sac* formed by excess of gas) coincides in general with a real boundary between the crystalline grains. The true boundary is merely the trace of a surface on the plane of casting, but it may be broadened out in this way, by the presence of gas, into a shallow channel of considerable width. It is only in certain conditions of temperature, on the part of the metal and of the body against which it is cast, that any marked development of such channels is obtained. Under most conditions, however, it is easy to distinguish the intergranular boundaries in the cast surface, either by the presence of some gas there or by slight differences of level between one grain and the next.

Occasionally the faces of some of the grains in the surface cast against glass are covered with a number of very minute pits, whose true character appears only under a magnification of about 1000 diameters. They are then seen to be pits of definite geometrical form both as to outline on the surface and as to inner facets. Figs. 7, 8, and 9 are photographs of these pits in glass-cast cadmium. It will be seen that they are systems of geometrical figures which remain similar and similarly situated over the entire surface of a single grain, but change in character from one grain to the next. These pits appear to be excessively small bubbles or blow-holes which have taken a geometrical shape, forming, in fact, negative crystals. During the crystallisation the crystalline elements have built themselves around the gas bubbles in regular orientation, finally leaving the pits as we see them. In support of this view the appearance seen on fig. 8 may be cited; the pits are seen to be surrounded by a halo or circular patch of bright surface—due apparently to the absorption by these larger geometrical bubbles of the numerous tiny bubbles that dot the surface elsewhere.

The photographs show these "air-pits" in cadmium cast against glass under a magnification in most cases of 1000 diameters, and in one case (fig. 9) of 4200

diameters. The characteristic of the pits is that they are similar and similarly oriented over any one grain, but on passing from one grain to another, across a boundary, the orientation of the pit is found to have changed. Good examples of this are seen in fig. 7, where the boundaries are widened out into channels through the presence there of air or gas in the manner described above. This characteristic of the air-pits is, of course, in complete conformity with the view already stated of the crystalline structure of metals. Additional photographs of air-pits in cadmium are shown in another connection in figs. 26, 27, and 28 (Plates 22 and 23).

Examination of the air-pits in cadmium shows that the forms may be accounted for as sections of hexagonal prisms. It may be concluded that each crystalline element of which the grains of cadmium are built up is a hexagonal prism with plane base.*

These air-pits are not very readily developed, and the precise conditions which determine their appearance are not easily specified. Many specimens of the metal may be cast without obtaining them. That they are not, however, peculiar to cadmium is certain, for we have found them also in tin and in zinc. Fig. 10 shows them in a glass-cast surface of tin.

The same photograph illustrates another interesting feature. The surface of the tin is seen to be covered with a multitude of small dark crystals irregularly disposed. These are evidently inclusions of some foreign matter, which we conjecture to have been sulphide, because it was observed that they appeared in large numbers after the metal had, during melting, been directly exposed to a gas flame. The foreign crystals have no definite orientation, and are quite independent of the orientation of the metal within the grains in which they are embedded. The crystallisation of the metal has proceeded around them without check or disturbance, just as in iron containing slag the growth of each crystalline grain ignores the presence of that impurity. It is well known that a slag band is often seen running right through a crystalline grain without affecting the uniformity of orientation of the elements of which the grain is built up.

Although it must be admitted that a really good development of geometrical bubbles such as those shown in the photographs is exceptional and cannot as yet be reproduced at will, the authors have observed that nearly all bubbles or blow-holes found on surfaces prepared in this way show a distinct tendency to geometrical shapes. A truly round bubble is rarely or never found, and even the larger bubbles often show a multitude of distinct facets reflecting light at different angles.

The occurrence of such geometrical pits in surfaces of metals that have never been polished or etched may be taken as very strong evidence in support of the view that

* It may be added in this connection that BEHRENS remarks on the frequency of six-sided forms in the polygonal boundaries of the crystalline grains of cadmium. The form of boundary is, however, of little service in determining the character of the crystallisations within the grain. (See his work 'Das Microscopische Gefüge der Metalle und Legierungen,' Leipzig, 1894.)

the crystalline grains of metals are built up of crystalline elements which are similarly oriented throughout the mass of each grain.

The experiments now to be described were intended to throw light on the nature of plastic strain in metals, and the results obtained are interpreted by the aid of the theory of the crystalline structure of metals, of which an outline has been stated at the beginning of this paper. Their complete agreement with that theory affords further confirmation of its truth.

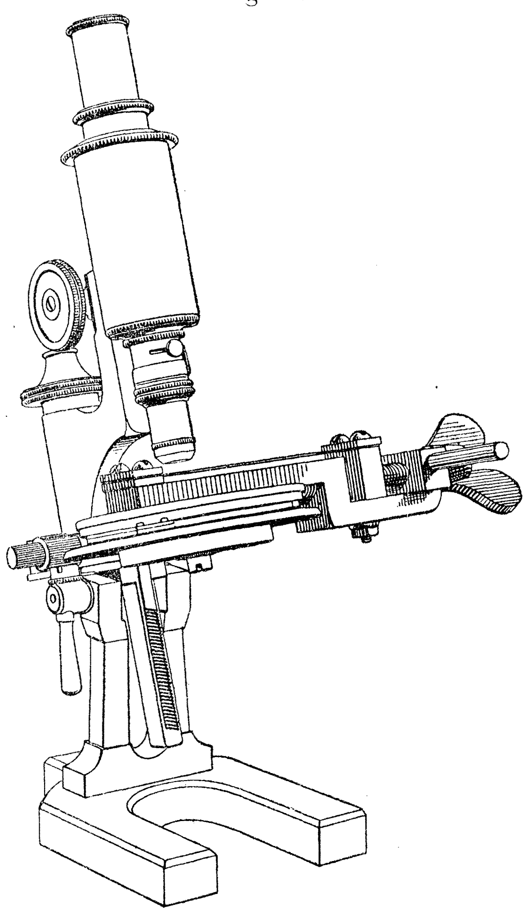
It has long been known that when a specimen of iron or steel with a bright smooth surface is strained sufficiently to give it permanent set the smoothness of the surface is destroyed. A microscopic examination of the surface shows, as CHARPY has pointed out, that the crystalline grains become visibly differentiated from one another by straining, and the effect is in this respect not unlike that which etching would have produced. There is, however, a further effect of straining, which will be described immediately.

It is also well known that when a piece of severely-strained metal is polished and etched, as for instance a bar which has had its section reduced by hammering or rolling in the cold state, the crystalline grains are found to have changed their form. They are lengthened in the direction in which the piece was extended and shortened in the direction in which the section has contracted. Accordingly, a severely-strained piece is readily recognised on polishing and etching it, on account of the shape of its crystalline grains. In the strained specimen these are found to have a direction of predominating length according to the direction of strain, while in the unstrained specimen there is no direction of predominating length. Further, it is well known that in a strained specimen elongated grains are not found after the strained state has been relieved by annealing. The effect of rolling or hammering is often spoken of as a conversion of the metal from a crystalline to a "fibrous" state. In the present writers' view this language is misleading, and the physical conception underlying it is a mistaken one.

In the first experiments on the effects of strain we aimed at keeping a particular place on the polished and etched surface of the specimen under continuous observation while the specimen was being strained. This was accomplished by constructing a small straining machine which could be attached to the stage of the microscope, and by which strips of sheet metal could be gradually extended until they broke. Fig. 11 shows the arrangement which was used. The stress was applied by a screw which could be turned by hand while the specimen was under observation, and any displacement of the particular grains on which the microscope was focussed could be made good by means of the traversing screws in the mechanical stage. With this apparatus it was easy to keep the same group of crystalline grains under observation from the first application of stress until the specimen was broken, and to obtain photographs of the same group at any number of stages during the strain. The first specimens observed in this way were strips of sheet iron, of the nearly pure kind supplied for

use in electrical transformers. The following account of what we have observed may be read as applying not only to iron but to other metals. Within the limit of elasticity no effects of strain are detected, but when the yield point is reached a remarkable change is seen on the surface of the crystalline grains. As soon as plastic deformation begins the faces of the grains show fine black lines, and as the strain increases these lines increase in number; they are more or less straight and parallel in each grain, but are differently directed in different grains. The first lines to appear are those approximately transverse to the pull, but as the strain increases systems of

Fig. 11.



inclined lines appear on other grains. With further straining some of the grains begin to show more than one system of such lines, and eventually two, three, and even four systems of intersecting lines on a single grain may be seen.

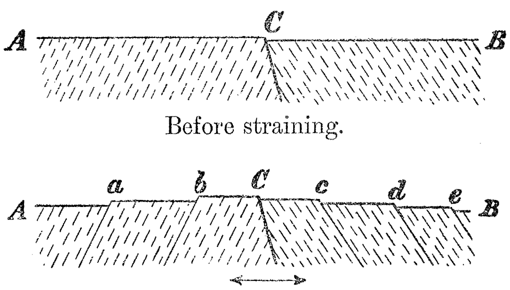
A characteristic example of these lines as exhibited by iron is shown in fig. 12, which is a photograph of a piece of Swedish iron strained by pull. Figs. 13 and 14 are two views of the same group of crystalline grains in another piece of Swedish iron, fig. 13 being taken before straining, and fig. 14 after a considerable amount of straining. When the piece is much strained the surface becomes so rough as to make it difficult to secure a satisfactory photograph.

The appearance of the grains after straining so closely resembles that of a crevassed glacier that the black lines might be taken for cracks. But from the outset it was clear that they could not be actual fissures. A piece of strained iron, when it has been allowed to rest for a time, or has been heated to 100° C.,* recovers its original elasticity and more than its original strength, yet the dark lines do not disappear under such treatment. Further, if a specimen showing these lines be re-polished the lines disappear, and even light etching does not reproduce lines of the same nature.

The real character of the lines is apparent when the crystalline constitution of each grain is considered. They are not cracks but steps in the surface. These steps are due to slips along the cleavage or gliding planes of the crystals.†

The diagram, fig. 15, is intended to represent a section through the upper part of two contiguous surface grains, having cleavage or gliding places as indicated by the dotted lines, A B being a portion of the polished surface, C being the junction between the two grains.

Fig. 15.



After straining.

When the metal is strained beyond its elastic limit, as say by a pull in the direction of the arrows, yielding takes place by finite amounts of slips at a limited number of places, in the manner shown at *a*, *b*, *c*, *d*, *e*. This exposes short portions of inclined cleavage or gliding surfaces, and when viewed in the microscope under normally incident light these surfaces appear black because they return no light to the microscope. They consequently show as dark lines or narrow bands extending over the polished surface in directions which depend on the intersection of the polished surface with the surfaces of slip.

The correctness of this view is demonstrated when these bands are examined under oblique light. When the light is incident at only a small angle to the polished surface, that surface appears for the most part dark; but here and there a system of the parallel bands shines out brilliantly in consequence of the short cleavage surfaces which constitute the bands having the proper inclination for reflecting light into the microscope. The groups of bright bands which are seen under oblique light are

* See J. MUIR "On the Recovery of Iron from Overstrain," 'Phil. Trans.,' A, 1899.

† See 'Roy. Soc. Proc.,' March 16, 1899 (vol. 65, p. 85), where the authors have published a preliminary account of some of these observations.

readily observed under the microscope to be exactly coincident with the black bands seen under vertical illumination. Figs. 16 and 17 are photographs of the same strained crystalline grains of iron under vertical light and under oblique light.

Rotation of the stage upon which the strained specimen is fixed makes the bands on one or another of the grains flash out successively with kaleidoscopic effect. When the specimen is rotated through 180° from the position in which the lines show brightly on one particular grain, the lines on that grain do not shine out again, though they may be visible as black lines on a very faintly luminous background; this is important as proving that the lines are not due to either furrows or ridges, but to steps in the surface. In this respect there is a striking contrast between the slip-bands and any accidental furrows or scratches which may have been left on the specimen through imperfect polishing.

Incidentally, fig. 17 illustrates the fact that oblique light picks out the boundaries of the crystalline grains, showing that these boundaries are marked by inclined surfaces connecting grains whose faces are at different levels. This is observed also in the etched surface of the metal before straining. The boundaries, which appear dark under vertical light, are bright on one side of each crystalline grain when the light falls with grazing incidence from one side; but the sloping surfaces which mark the boundaries between the grains have not the sharply-defined inclination of the slip-surfaces. The lines due to slip-bands on one or more grains will shine out brightly when the light has a particular angle of incidence, and will vanish when the incidence is slightly changed. The boundaries are generally not so bright, but remain visible under a considerable range of incidence.

Figs. 18, 19, and 20 present a striking example of the kaleidoscopic effect under oblique light just referred to. Here the metal is lead, the surface has been obtained by allowing molten lead to solidify on a smooth glass plate, and the metal has been strained by bending. The figures show the appearance under vertical light and also under two different incidences of oblique light. Figs. 21 and 22 show another example of strained lead under vertical and oblique light.

In their preliminary notice* of some of the present results (communicated to the Royal Society on March 16, 1899) the authors have applied the name "slip-bands" to the lines developed on metallic surfaces by plastic strain, and in what follows they will be referred to under that name.†

So far as the writers' observations go it appears that slip-bands occur in all metals

* "Experiments in Micro-metallurgy: Effects of Strain," 'Proc. Roy. Soc.,' vol. 65, p. 85. Since writing that paper the authors' attention has been directed to the following remark by Mr. STEAD:—"It would appear that there is a tendency for iron to etch out into thin plates, and when such etched specimens are distorted or pulled out for these etched plates to slide over one another" ("On Brittleness Produced in Soft Steel by Annealing," 'Journal of the Iron and Steel Institute,' 1898). It will, however, be shown presently that the development of slip-bands is independent of any previous etching.

† "Experiments in Micro-metallurgy: Effects of Strain," EWING and ROSENHAIN, 'Roy. Soc. Proc.,' 1899, vol. 65, p. 85.

as soon as plastic deformation takes place. They have been observed in specimens of platinum, gold, silver, copper, lead, zinc, tin, cadmium, bismuth, aluminium, iron, and nickel, as well as in steel, brass, bronze, and other alloys. In the case of iron it was proved definitely that under tensile stress the bands appear as soon as the yield point is passed. For this experiment a flat was polished on the side of a test-piece, which was strained in a 50-ton testing-machine, and the surface was kept under observation, during the application of the stress, by means of a microscope hung from the bar itself.

Slip-bands are developed by all kinds of strain involving permanent deformation of the piece. A microscopic inspection of the surface after straining does not enable us to detect whether the deformation has been caused by tension, compression, bending, or torsion, but the appearance depends very much on the amount of strain that has taken place. The more severely the specimen has been strained the greater is the number of slip-bands developed. After slight straining there is generally only one system of bands to be seen on each crystalline grain, but as many as four such systems intersecting one another may come into view after severe straining. Fig. 23 (Plate 21) is a photograph of strained lead, showing four systems of slip-bands.

The general appearance of the slip-bands is different in different metals. In lead they are particularly straight, even under extreme magnification, as is illustrated in fig. 24. In silver there is a tendency to more wavy outlines, as appears in fig. 25, Plate 22, but in gold the lines are as straight as those in lead. In iron the lines tend, as a rule, to be rather wavy, and to fork and branch. Examples of slips in this metal have already been given in figs. 12, 14, and 16; others have been given in the preliminary notice referred to above.*

In gold, lead, and other metals showing straight slip-bands it is easy to distinguish well-marked steps where intersecting systems cross. Fig. 24 is a characteristic example.

In several specimens of lead, prepared by casting against glass, a peculiarity was noticed which forms an apparent exception to the statement made above that slip-bands which shine out under oblique light at one particular incidence do not reappear when the incidence is changed (*i.e.*, the specimen rotated) by 180°. The specimens in question were examined under oblique light with an objective of 16 millims. focus, giving a magnification of 100 diameters. On rotating the stage carrying the specimen the slip-bands on one crystalline grain were found to shine out strongly in two positions, very nearly 180° apart. Under this low magnification it seemed that identical bands were visible in both positions; but on applying a power of 2000 diameters with a combination of "vertical" light and an oblique beam of grazing incidence from an arc lamp it was seen that there were really two systems of parallel slip-bands on the same crystalline grain, and that only one of them was picked out by the oblique light. In the other system of slip-bands the slope of the cleavage surfaces exposed by the slips was inclined away from the source of light, and consequently remained dark. The

* 'Roy. Soc. Proc.,' vol. 65, Plates 1–5.

explanation, then, is that in this grain the crystalline elements are oriented in such a way that the intersection of two sets of cleavage or gliding planes is parallel to the surface, and consequently their traces on the surface are parallel to one another. This seems to be an accidental occurrence, possibly favoured by the condition under which the specimen crystallised, namely in contact with cold glass. In many other instances a more or less close approximation to such parallelism has been observed, resulting in systems of slip-bands intersecting at a very small angle; in that case the two positions where slip-bands appear under oblique light are nearly, but not exactly, 180° apart. Seen under vertical light, with low magnification, such intersecting systems produce the appearance which is exemplified in the central grain in fig. 18, Plate 19.

The relation of slip-bands to the geometrical air-pits in cadmium is illustrated by the photographs, figs. 26, 27, and 28. In these examples the metal was cast against glass in such a way as to produce air-pits, and was then strained sufficiently to develop slip-bands. It appears that the slip-bands are always parallel to one side of the geometrical pits—the two phenomena thus confirming the views which have been advanced above as to the crystalline structure of the metal. Figs. 29 and 30 show the relation of slip-bands to geometrical etched pits in iron. It will be observed that the slips are not generally parallel to a side of the etched figures, but in specimens that have been more severely strained than those here illustrated, one set of slip-bands in each grain is generally found to be parallel to one side of the etched pits, while the other systems intersect these sides diagonally. The observations point to the conclusion that in iron slipping occurs most readily along the octahedral planes, although slips parallel to the sides of the cubical crystals are also found.

The development of slip-bands in strained metal throws what appears to us to be a new light on the character of plastic strain. Plasticity is due to the occurrence of these slips. When metals are strained beyond their limit of elasticity the deformation occurs through sliding over one another of the elementary portions of which each crystalline grain is built up.

The sliding which gives rise to slip-bands is of finite amount, and occurs at a limited number of places. "Flow" or plastic strain in metals is not a homogeneous shear such as occurs in the flow of a viscous fluid, but is the result of a limited number of separate slips.

The conception that metals adapt themselves to the new shapes imposed upon them when they undergo plastic deformation by means of slips along cleavage or gliding planes within each crystalline grain, leads naturally to the supposition that the crystalline elements themselves undergo no deformation in this process. The portions of the metal between one surface of slip and the next may remain undeformed, except elastically, under all stresses. The effect of a stress sufficient to produce plastic strain is analogous to that of a tractive force overcoming the static friction between two surfaces.

If we assume that plastic strain takes place solely by these slips, it follows that the ultimate crystalline elements should always remain parallel to themselves. The orientation of the elements would remain uniform throughout the mass of one grain, however much the outline of that grain were distorted by slips occurring within it. In other words, the crystalline structure of a metal should survive even the severest strain.

This conclusion is borne out by the fact that in metals which have been much strained we find evidence of crystalline structure similar to that which is found in unstrained metal.

Taking this evidence in the same order as before, we would refer first to the appearance which is presented in severely strained metal, by a polished and etched section when seen under oblique light. We have examined a bar of fine Swedish iron (kindly supplied by Messrs. EDGAR ALLEN and Co.), which had been for the purpose of these experiments rolled in the cold state from a diameter of three-quarters of an inch to a diameter of half an inch, and had not been subsequently heated. A longitudinal section of this cold-rolled bar showed a great lengthening of the crystalline grains in the direction of rolling, and even in the transverse section it was obvious that the grains had been much distorted, though there was no direction of predominant length. Under oblique light both sections (longitudinal and transverse) exhibit the effect described above for unstrained metal—the grains are distinguished from one another by differences of brightness, which vary when the incidence of the light is altered, and this brightness is uniform over the entire surface of each grain. As in the case of unstrained metal, we regard this as evidence of the uniform orientation of the crystalline elements throughout each grain. Fig. 31, Plate 23, is a photograph under oblique light of a specimen of this bar cut transversely, and polished and etched. It illustrates the uniform brightness of each grain, due to uniform orientation. Similar characteristics have been observed in many other specimens of severely strained metal.

Another line of evidence in proof of the persistence of crystalline structure after severe straining is afforded when a polished specimen of, say, cold-rolled iron is subjected to a slight further strain. The slip-bands appear as they would have done had the specimen never been strained before. The general features are much the same as in annealed metal, but they show on the whole a greater tendency towards sudden steps and branches. This difference in the character of the slips may be connected with the well-known fact that such strained material is considerably harder, in the sense of having a higher yield-point and less capability of plastic deformation than it shows in the virgin or annealed state, and also with our own observation that the slip-bands are much more straight and regular in very plastic metals, such as lead, gold, and copper, than in harder metals like iron and nickel. The mere fact that finite slips occur at intervals throughout the grain implies that it is easier for sliding to take place over certain surfaces than it is over others. The surface on which

uniform slip occurs is not necessarily plane; it may be the trace of a straight line moving parallel to itself; a line which is in the direction of slip and always lies parallel to one of the cleavage planes. For convenience in argument we may for the moment assume that the surfaces of easiest sliding are determined by some accident, such as the presence there of minute layers of some impurity, such as occluded gas. If, as the straightness of the slip-bands seems to indicate, these surfaces are true planes in plastic metals like lead or gold (so far as each individual grain is concerned), sliding might take place in two directions on each of these planes. But when sliding has once taken place, the intersecting layers of impurity would no longer be distributed over planes, and further sliding on transverse planes would necessitate the starting of fresh slips in surfaces that had no special tendency to facilitate sliding. This suggests how such a metal may be hardened by previous straining; and how, also, the slip-bands formed on re-straining a piece of metal hardened in this way would be less straight and more liable to sudden steps and branches than those that are found in the virgin material; the slips would, as far as possible, follow the old surfaces of easy sliding, but these would now be stepped instead of plane as before.

A striking proof of the persistence of crystalline structure in metals which have been submitted to severe distortion is found in the existence of geometrical etched pits. These are readily developed in sections cut from cold-rolled iron, and they differ in no way from the etched pits developed in the virgin material; like these, they appear as similar and similarly oriented geometrical figures over the face of each grain. Fig. 32 is the photograph of a group of crystalline grains in the specimen of cold-rolled Swedish iron referred to above (cold-rolled from three-quarters of an inch to half an inch diameter). Among them is a large grain (showing light in the figure) with an outline so unlike those found in unstrained metal that its form is evidently due to violent distortion in the process of rolling. The face of this grain is covered with minute etched pits, and an examination of these under high powers shows that they have preserved their similarity of shape and orientation in spite of the violent distortion which the grain, as a whole, has undergone. Fig. 33 is a photograph under 800 diameters of a portion of the large grain in question, which appears near the middle of fig. 32.

From the various lines of evidence here indicated we conclude that the characteristic crystalline structure of metals is not destroyed by strain, no matter how severe, and that plastic deformation occurs by means of slips along the cleavage or gliding planes of the crystalline grains, the crystalline elements which build up each grain remaining unaltered both as to shape and orientation. This statement, however, is subject to the following qualification. We have found in certain metals, notably copper, gold, silver, lead, cadmium, tin, zinc, and nickel, that twin crystals are liable to be developed by straining. Hence in such cases it is not exact to say that straining produces no change in the orientation of the crystalline elements, for twinning implies a rotation of one group of elements with respect to the rest through a

definite angle. The twinning which we have found in many strained metals corresponds to the twinning observed in calcite by BAUMHAUER and REUSCH, and subsequently produced in isolated crystals of antimony and bismuth by MUGGE.*

BAUMHAUER found that by forcing a knife blade into a crystal of calcite at the proper angle a portion of the crystal could be made to swing over into the twinned position. This implies a corresponding change of orientation in the crystalline elements. The experiment may be said to afford an example of plasticity in a crystal, but it is not entirely analogous to the plasticity by pure sliding which is found in iron and in most other metallic crystals. In the process of twinning by strain there is both slip and rotation of the elements.

The existence of twin crystals in certain metals became apparent when systems of slip-bands were found like those shown in figs. 34, 35, and 36. These are photographs from specimens of copper. They show that certain of the crystalline grains are crossed by twin lamellæ, the twin planes being defined by a sudden change in the direction of the slip-bands. Where several such twin lamellæ occur in one crystalline grain, we have a periodic structure with alternate systems of parallel slip-bands. The change of orientation in passing from one lamella to another is constant. It is clear that in these examples we have true cases of twin crystallisation. An example of twinning in gold, as seen under vertical light, is given in fig. 37, and fig. 38 is a photograph of twins in gold, seen under oblique light.

The question arose whether these twin crystals were a feature in the primitive crystallisation of the metal, or whether they were subsequently produced as a consequence of strain. They were first seen in wrought copper (namely in a piece of rolled plate), which had been raised to a bright red heat before polishing. We next examined specimens of copper, gold, silver, and lead, each in the cast state, and in none of these found any appearance of twinning. For the purposes of this examination only a slight strain was applied. The same pieces were then wrought, that is to say they were severely strained (namely, by cold hammering) and they were again examined both before and after annealing at a red heat. The result showed that the violent strain produced by working the metal had developed twins in specimens where none could be seen before, and that the twins were still found in the wrought specimens after annealing. Fig. 39 is a photograph of a "twin" in cold-hammered copper (not heated after hammering); incidentally it illustrates the persistence of crystalline structure after violent deformation. Still more striking in this respect is the appearance shown in fig. 40. The specimen in this instance was an ordinary piece of plumber's sheet lead; the surface was scraped bright with a knife, and was then squeezed against a piece of plate-glass in a vice, thus producing a beautiful surface. The specimen was then very slightly bent in the fingers to develop slip-bands, and on examination under a high power it showed the appearance reproduced in the photograph.

* See P. GROTH'S 'Physikalische Krystallographie.' VOSS, Leipzig.

Twinning, as revealed by slip-bands, has been observed in nickel; in this case the specimen was a virgin casting, but the twin (shown in the photograph, fig. 41) was observed only after very severe straining, and was, in all probability, produced by that straining.

In zinc, tin, and cadmium twins either occur very freely in the cast metal, or else are very readily produced by the slight strain which is applied to develop slip-bands. Surfaces of these metals, produced by casting against glass, show twin bands even under fairly low powers when the specimen is slightly bent; the twin bands then appear as shaded bands running across the crystalline grains. Very frequently the twin bands run on continuously across two or more grains, with more or less change in direction when they cross a boundary.

A specimen of cadmium showing this feature is photographed in fig. 42. This particular specimen presents another peculiarity; it was prepared by casting against glass, and in this instance the glass surface was intentionally given a considerable slope, with the result that the metal solidified in a long strip while it was running down the glass. On examining the under face of this strip two modes of crystallisation were observed. Part of the surface there showed a very small structure with no direction of greatest length. On another part there were large grains very considerably longer in the direction of the length of the strip than in a transverse direction. The photograph, fig. 42, is taken from an area showing these long grains. When the piece was strained by bending, twin lamellæ appeared in a more or less transverse direction, passing across from one elongated grain to the next with only a slight change in direction. The twin band in one grain is associated with a twin band in a neighbouring grain, the bands being continuous except for a change of direction as they pass from grain to grain.

We have observed twinning in gold, silver, copper, lead, nickel, zinc, tin, and cadmium. It does not appear to occur in iron.

The facility with which most metals undergo twinning as a consequence of strain shows that there are in general two modes by which plastic yielding takes place in an aggregate of crystals. One is by simple slips, where the movements of the crystalline elements are purely translatory, and their orientation is preserved unchanged. The other is by twinning, when rotation occurs through an angle which is the same for each molecule in the twinned group. Both modes are often found in a single specimen of metal, and even in a single crystalline grain. Thus, in gold or copper, it is very usual to find, on examining a strained specimen that one portion of a grain is covered with simple slip lines, while another portion of the same grain shows one or more lamellæ which are twinned with respect to the rest of the grain.

On surfaces prepared by casting against glass, particularly with cadmium, but also with zinc and tin, a curious feature often occurs which is closely associated with the facility these metals show in developing twins. The appearance in question is that of an apparent duplication of the inter-granular boundaries, as seen in the cadmium

casting, fig. 43. The second system of boundaries consists, like the first, in polygonal markings, and has such an obvious relation to the first that it almost appears as though the upper layer of crystalline grains were transparent, and that we were seeing their lower edges. To decide as to which of the markings on the surface constituted the true surface boundaries, two methods were available: etching with an acid and slightly straining the specimen so as to develop the slip-bands. The latter method is much the more instructive, and its results are confirmed by the etching process. When a specimen having this characteristic was strained, it was seen at once that some of the apparent boundaries were consistently ignored by the slip-bands, the others being the real junction lines of the grains. But the true nature of the pseudo-boundaries comes out on examining them under a high power. Although under low powers there is no obvious difference in definition between the genuine and pseudo-boundaries, under greater magnifications it becomes impossible to focus the pseudo-boundaries at all—they are seen to be more or less ill-defined slopes or changes of level, whereas the real boundaries are sharply defined. In general the real boundaries show some accumulation of gas bubbles along them, and they are never crossed by slip-bands. The pseudo-boundaries are found to consist in small variations of level in the surfaces of the grains in which they occur. Fig. 44 is a high-power photograph of a set of real and pseudo-boundaries showing slip-bands.

It will be noticed that on the two sides of a real boundary the slip-bands are independent of one another, whereas the slip-bands cross a pseudo-boundary with only a slight change of inclination, which is to be ascribed to the fact that the surface under examination is not a true plane. There is a slight slope on each side of the pseudo-boundary, and the lines are consequently more or less inclined to one another. Again, as we have noticed in other examples, the slope is not as a rule constant and hence the lines are slightly curved.

An explanation of this appearance of pseudo-boundaries is, we think, to be found in the strains set up by contraction on cooling. If we suppose the outer layer of crystals to cool more rapidly than the inner ones, the resulting contraction will drive the projecting edges of the lower layer into the outside grains and thus cause slight local deformation, which will project itself on the surface, probably by means of twin bands running through the grains and appearing on the surface. The effect resembles that of a Japanese "magic" mirror, in which slight inequalities of the surface, corresponding to a pattern behind, cause light reflected from the mirror to produce an image in which a ghost of the pattern may be traced.

The foregoing conclusions refer to experiments on pure or nearly pure metals. We have also examined the effects of strain on various alloys. The micro-structure of alloys has received attention at the hands of most of the workers already named, especially BEHRENS, CHARPY, GUILLEMIN, OSMOND, ROBERTS-AUSTEN, and STEAD. Our observations have been directed towards supplementing theirs, in respect particularly of the effects of strain.

The experiments on iron were extended to certain steels. In very mild steel slip-bands can be readily observed in what are generally called the "ferrite" areas, which remain white after light etching. This is shown in fig. 45. The first effect of strain is to develop the inter-granular junctions in these white areas, then more severe straining makes the slip-bands appear. In steels containing larger proportions of carbon, the scale of the granular structure of the "ferrite" diminishes and the slip-bands become correspondingly minute, requiring the highest powers of the microscope for their observation. We have not been able to observe anything of the nature of slip-bands in the dark or "pearlite" areas of steel, but the correspondence which has been recognised by OSMOND to exist between the structure of "pearlite" and that of typical eutectic alloys, taken with facts to be described below, points to the possibility that "pearlite" may also yield plastically by slipping.

Slip-bands have also been observed in various specimens of brass and bronze.

The behaviour of eutectic alloys under plastic strain is of special interest, because these bodies apparently differ so widely in structure from pure metals. Our observations have been made on the eutectics of lead-tin, copper-silver, and lead-bismuth. The micro-structure of such eutectics has been described by OSMOND.

Fig. 46 is from a specimen of lead-tin eutectic kindly prepared for us by Messrs. HEYCOCK and NEVILLE; the surface was obtained by casting against glass, and was lightly etched with a 1 per cent. solution of nitric acid. Figs. 47 and 48 illustrate the most obvious effect of strain on such structures; the surfaces have not been etched, the differentiation of the two constituents by differences of level being here entirely due to strain. It will be observed that the scale of this structure is similar to that of the slip-bands seen in pure metals, and examination of strained specimens shows that plastic yielding is associated with slips occurring between layers of the two constituents. A close examination of strained specimens has enabled us to detect slip-bands in the light-coloured constituent. By adopting the device of slow cooling, which has led to such excellent results in the hands of Messrs. HEYCOCK and NEVILLE, we have succeeded in producing specimens of eutectics in which the characteristic structure is developed upon a much larger scale. Fig. 49 exemplifies this in the eutectic of bismuth and lead, and shows slips which occur in the white constituent as a consequence of straining. This photograph illustrates a feature very characteristic of eutectic alloys; a parallel system of slip-bands extends over many patches of the white constituent, thus pointing to the fact that the crystalline elements are similarly oriented throughout considerable areas of at least one of the two constituents of the alloy. This suggests that the alloy as a whole has comparatively coarse granular structure, and the same conclusion is borne out by observing the general character of a surface under lower magnifications (such as 100 diameters), when its structure is revealed either by straining or etching. The surface is then seen to be divided into rather large more or less polygonal areas, each covered with a system of ribs radiating

from one point, giving an appearance which resembles roughly the ribs of an umbrella. Fig. 47 incidentally shows the boundary of two such areas.

In the course of experiments on the lead-bismuth eutectic, specimens were obtained showing comparatively large isolated crystallites. When the piece was strained these crystallites were found to exhibit slip-bands. Examples are given in figs. 50 and 51. These are interesting as showing the development of slip-bands in bodies which are evidently fully developed crystals, even as to external form.

A study of the micro-structure of alloys suggests a possible explanation of the peculiarities they present in regard to variation of electrical conductivity with temperature. The two constituents may behave individually as pure metals in this respect, but if their coefficients of expansion are different the closeness of the joints between them will depend on the temperature. Thus, if the more expansible metal exists as plates or separate pieces of any form within the other, the effect of heating will be to make the joints between the two conduct more readily, with the result of reducing the increase of resistance to which heating would otherwise give rise, and in extreme cases with the effect even of producing a negative temperature coefficient.

Reviewing the general results of the experiments, we consider that they establish the view that the structure of metals in general is crystalline, and remains crystalline when the form of the metal is altered by strain, plastic yielding being due to slips on cleavage or gliding planes within each individual crystalline grain, and partly (in some metals) to the production of twin crystals. In a pure metal, when straining is carried far enough to produce fracture, the crystalline grains suffer cleavage, and the cleavage surfaces thus developed give to the fracture its characteristically crystalline appearance. In impure metals fracture may occur through the parting of grains from one another at their boundaries. In both cases, however, the plastic yielding which precedes fracture takes place by slips in the manner we have described.

In conclusion we should like to express our indebtedness to Sir W. ROBERTS-AUSTEN, Mr. T. ANDREWS, and Professor ARNOLD, for giving us at the outset of our work the benefit of their large experience in preparing specimens of metals for microscopic examination. Messrs. HEYCOCK and NEVILLE and Mr. A. HUTCHINSON have assisted us materially by various suggestions, and by supplying specimens for examination. We have also to thank Mr. ANDREWS, Mr. STEAD, Mr. HADFIELD, Professor HICKS, and Messrs. EDGAR ALLEN and Co. for special specimens of iron.

The work described in this paper was carried out in the Engineering Laboratory at Cambridge.

To facilitate reference to the illustrations an index is added in which brief particulars are given of the subject of each photograph.

Explanation of Figures on the Plates.

Plates 15–28.

PLATE 15.

Fig. 2. Nearly pure commercial iron (transformer plate), polished and etched. Magnified 200 diameters, vertical illumination.

Fig. 3. Photograph of bismuth crystals, from a specimen in the Cambridge University Mineralogical Museum. $\frac{2}{5}$ths of full size.

Fig. 4. Facets on a crystalline grain of iron, produced by etching. These facets give rise to differences of brightness when the grains are seen under oblique illumination. Magnified 1500 diameters, vertical light.

PLATE 16.

Fig. 5. Etched pits in Swedish iron. 1000 diameters, vertical light.

Fig. 6. Surface of cadmium cast against glass, showing crystalline boundaries emphasized by air-channels. 100 diameters, vertical light.

Fig. 7. Air-pits on a glass-cast surface of cadmium. 1000 diameters, vertical light. Pits are shown on three crystals, having a different shape and orientation on each.

PLATE 17.

Fig. 8. Air-pits on a glass-cast surface of cadmium. 1000 diameters, vertical light. The pits are surrounded by halos due to the absorption of smaller bubbles by the pits.

Fig. 9. Similar pits to those in figs. 7 and 8, but more highly magnified—4200 diameters. The photograph shows that the pits have geometrical inner faces.

Fig. 10. Air-pits in glass-cast tin. Magnified 1000 diameters, vertical light. The irregularly oriented black patches are crystals of an impurity.

Fig. 12. Slip-bands in Swedish iron strained by tension. 400 diameters, vertical light. The photograph shows a feature that is frequently observed, viz., a tendency in the lines to become curved near the inter-crystalline boundaries, suggesting the existence of keyed steps at the boundaries.

PLATE 18.

Figs. 13 and 14. Two views of the same crystalline grains in iron before and after straining. Magnified 200 diameters, vertical light. Close comparison of

the two will show the amount by which the crystalline grains have been extended.

Fig. 16. Strained Swedish iron. Magnified 300 diameters, vertical light.

Fig. 17. The same field as in fig. 16, with the same magnification, but seen under oblique light. The slip-bands on a few grains only are picked out as bright bands.

PLATE 19.

Fig. 18. Slip-bands developed on a glass-cast surface of lead when strained by bending. Magnified 100 diameters, vertical light.

Fig. 19. The same field as in fig. 18, seen under oblique light.

PLATES 20 AND 21.

Fig. 20. The same field as in figs. 18 and 19, seen under oblique light after the stage carrying the specimen had been turned through about 15°.

Fig. 21. Slip-bands in lead. 100 diameters, vertical light.

Fig. 22. The same field as in fig. 21, seen under oblique light.

Fig. 23. Slip-bands in lead, showing four intersecting systems. 600 diameters, vertical light.

Fig. 24. Slip-bands in lead. 1000 diameters, vertical light. The photograph shows the straight slips and stepped intersections characteristic of this metal.

PLATE 22.

Fig. 25. Slip-bands in silver. Magnified 750 diameters, vertical light.

Fig. 26. Geometrical air-pits in glass-cast cadmium, slightly strained to show slip-bands. 1000 diameters, vertical light.

Fig. 27. Ditto.

PLATE 23.

Fig. 28. Ditto. See also remarks on Figs. 7, 8, and 9.

Fig. 29. Geometrical etched pits and slip-bands, produced by slight straining, in iron. 750 diameters, vertical light.

Fig. 30. Etched pits and slip-bands in iron. 1000 diameters, vertical light.

Fig. 31. Polished and etched section of cold-rolled Swedish iron. 45 diameters, oblique light, showing the differences of brightness on various grains and the uniform brightness over each individual grain.

PLATES 24 AND 25.

Fig. 32. Distorted crystalline grains in a transverse section of cold-rolled Swedish iron, also showing geometrical etched pits. 200 diameters, vertical light.

Fig. 33. A portion of the large distorted grain in Fig. 32, more highly magnified; the enlarged portion is at the angle of the distorted grain. 800 diameters, vertical light.

Figs. 34, 35, and 36. Slip-bands in twin crystals of copper. 1000 diameters, vertical light.

Fig. 37. Slip-bands in twin crystals of gold. 200 diameters, vertical light.

Fig. 38. Slip-bands in twin crystals in gold. 45 diameters, oblique light.

Fig. 39. Slip-bands in twin crystals of cold-hammered copper. 1000 diameters, vertical light.

PLATE 26.

Fig. 40. Slip-bands in twin crystals observed in a specimen of plumbers' sheet-lead. 1000 diameters, vertical light.

Fig. 41. Slip-bands and twinning in nickel. 1000 diameters, vertical light.

Fig. 42. Elongated crystalline grains in cadmium cast on a sloping surface of glass. Transverse twin bands developed by slight straining are seen to run across a number of adjacent grains, with slight changes of direction on crossing a boundary. 100 diameters, vertical light.

Fig. 43. Glass-cast surface of cadmium, showing double system of boundaries. 100 diameters, vertical light.

PLATES 27 AND 28.

Fig. 44. High-power appearance of real and pseudo-boundaries as indicated by slip-bands. 1000 diameters, vertical light.

Fig. 45. Strained mild-steel, showing "pearlite" patches and slips in "ferrite" areas. 1000 diameters, vertical light.

Fig. 46. Glass-cast and etched surface of lead-tin eutectic. 750 diameters, vertical light.

Figs. 47 and 48. Glass-cast and strained (but unetched) lead-tin eutectic. 750 diameters, vertical light.

Fig. 49. Slowly-cooled lead-bismuth eutectic, etched and strained, showing slip-bands. 1000 diameters, vertical light.

Figs. 50 and 51. Slip-bands in crystallites found in lead-bismuth alloy. 1000 diameters, vertical light.

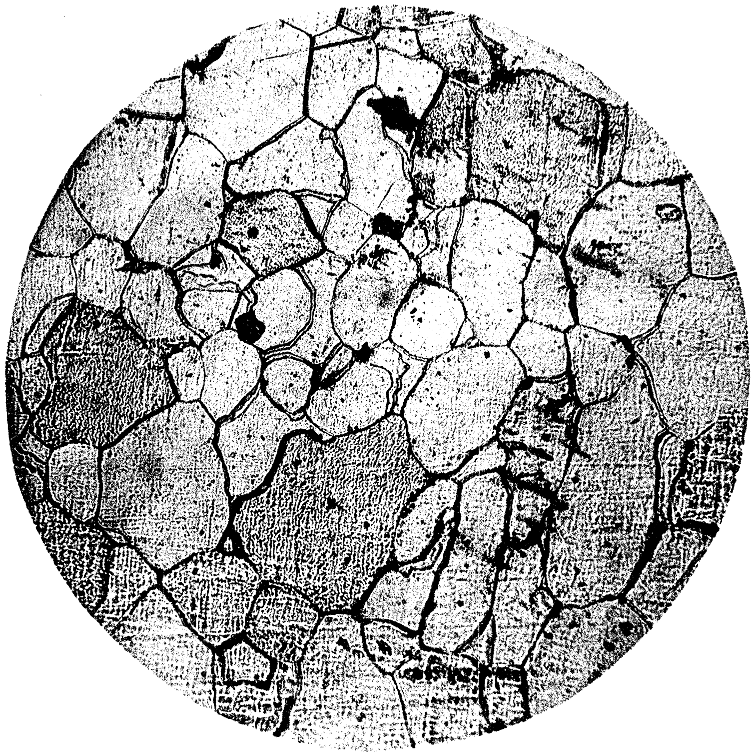


Fig. 2. IRON × 200.

Fig. 3. BISMUTH × $\frac{2}{5}$.

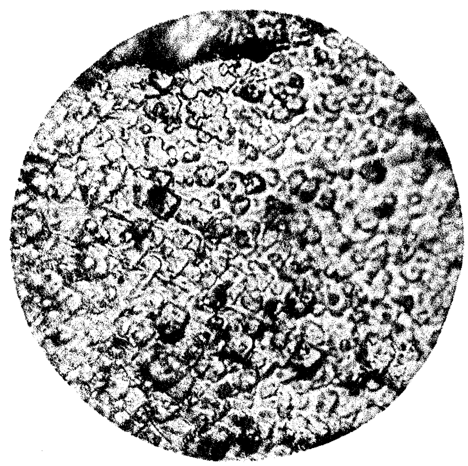


Fig. 4 IRON × 1500.

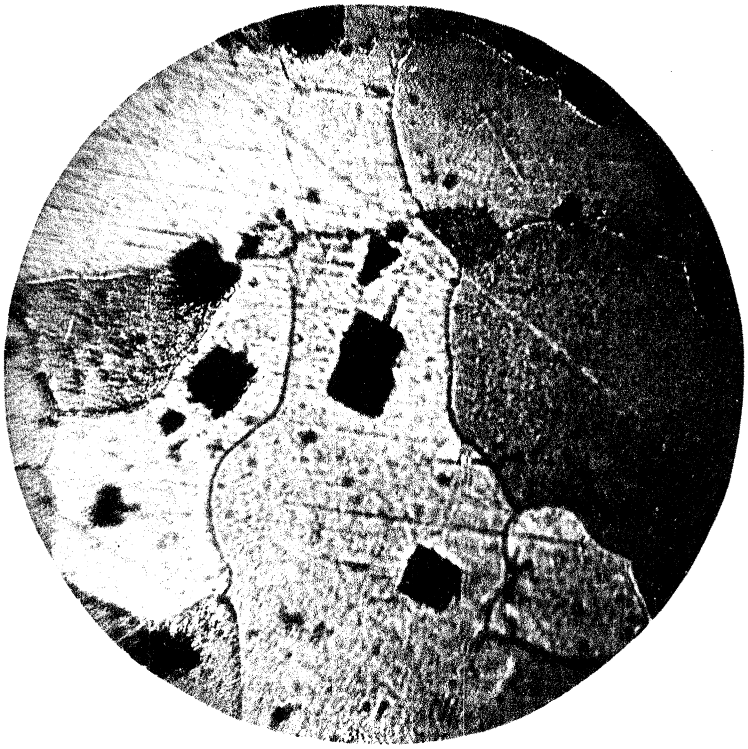


Fig. 5. Iron × 1000.

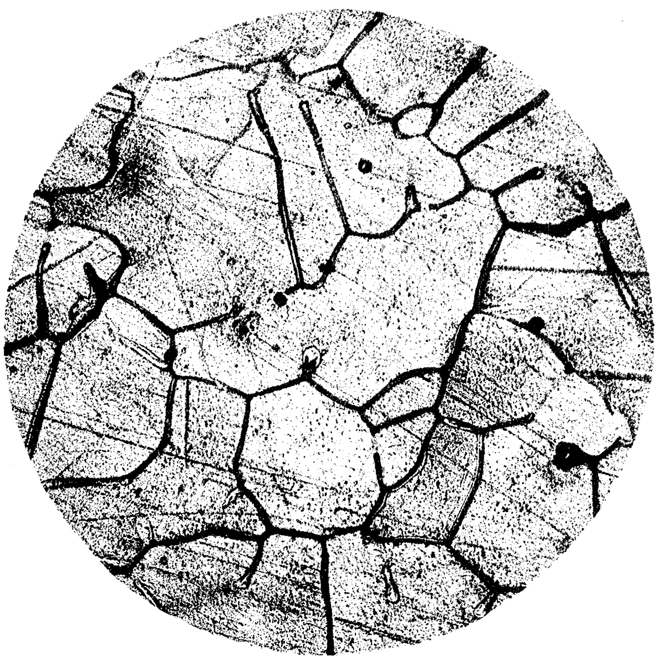


Fig. 6. Cadmium × 100.

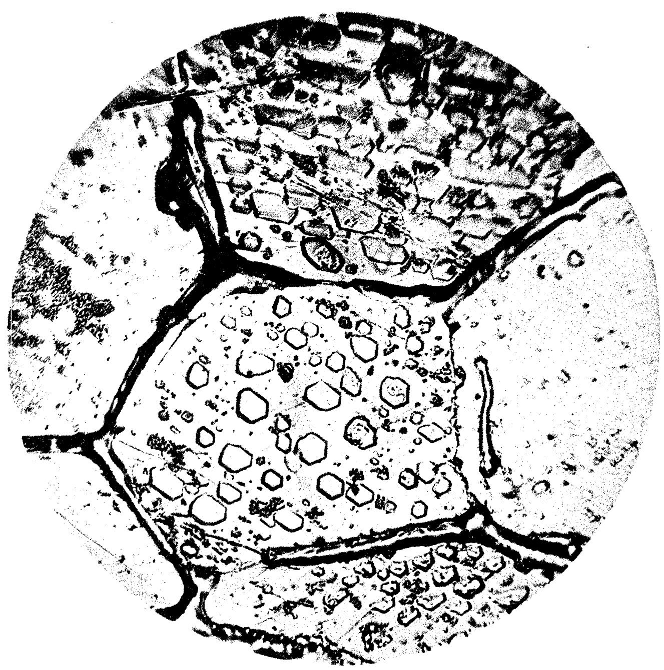


Fig. 7. Cadmium × 1000

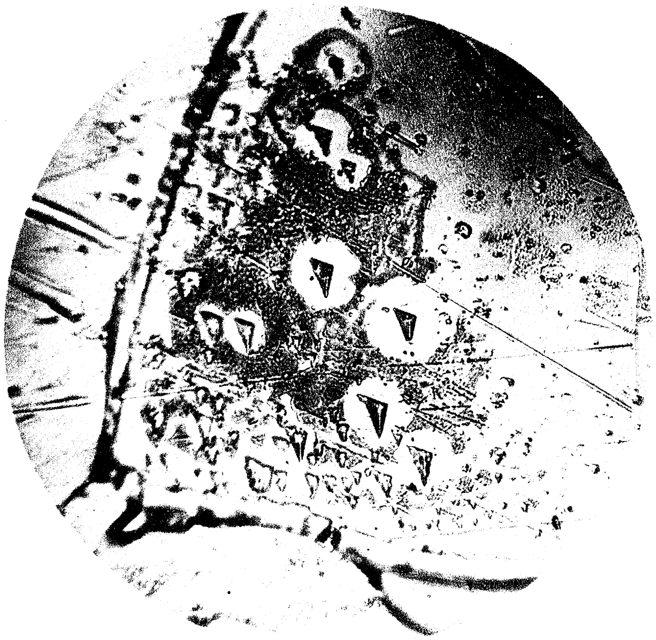


Fig. 8. CADMIUM × 1000.

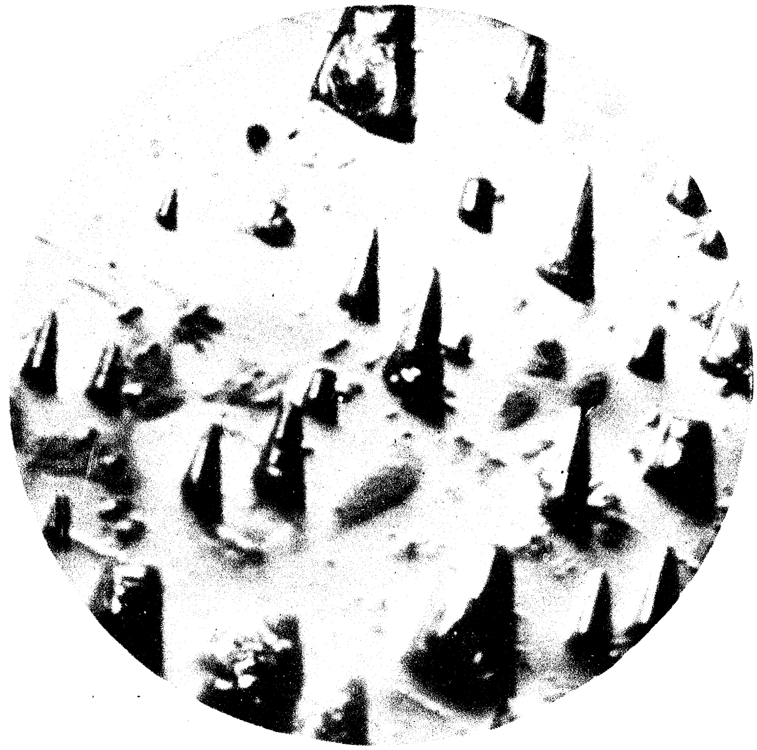


Fig. 9. CADMIUM × 4200.

Fig. 10. TIN × 1000.

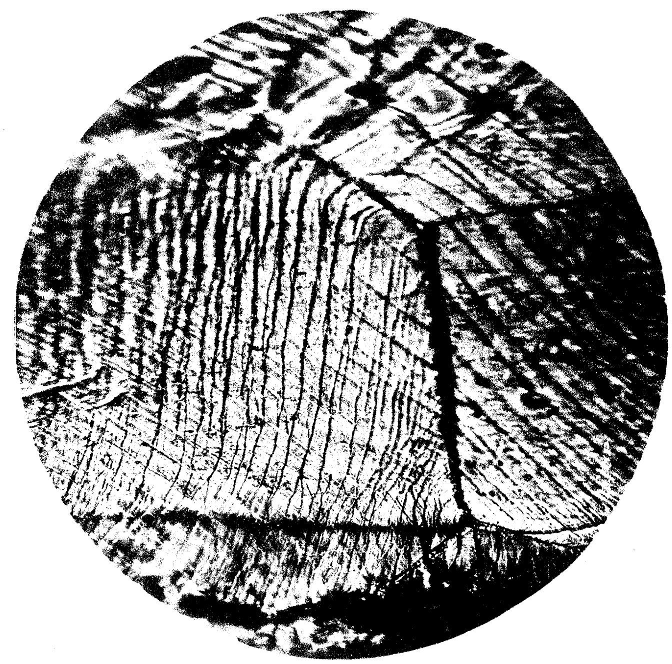


Fig. 12. IRON × 400

Fig. 13. Iron × 200.

Fig. 14. Iron × 200.

Fig. 16. Iron × 300.

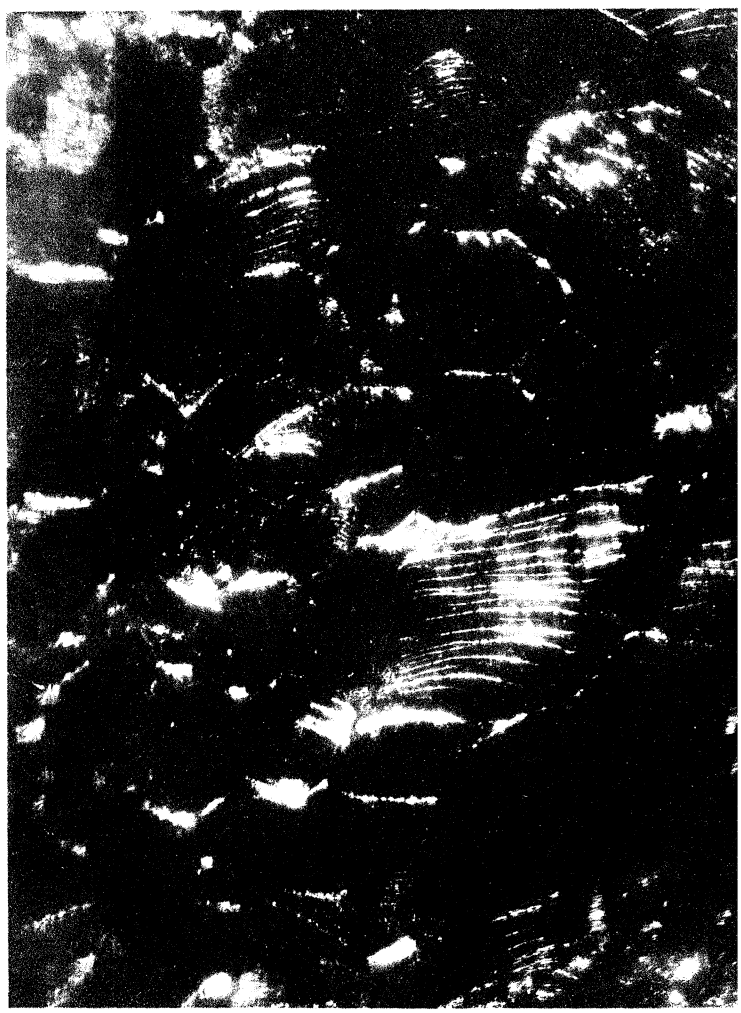


Fig. 17. Iron × 300.

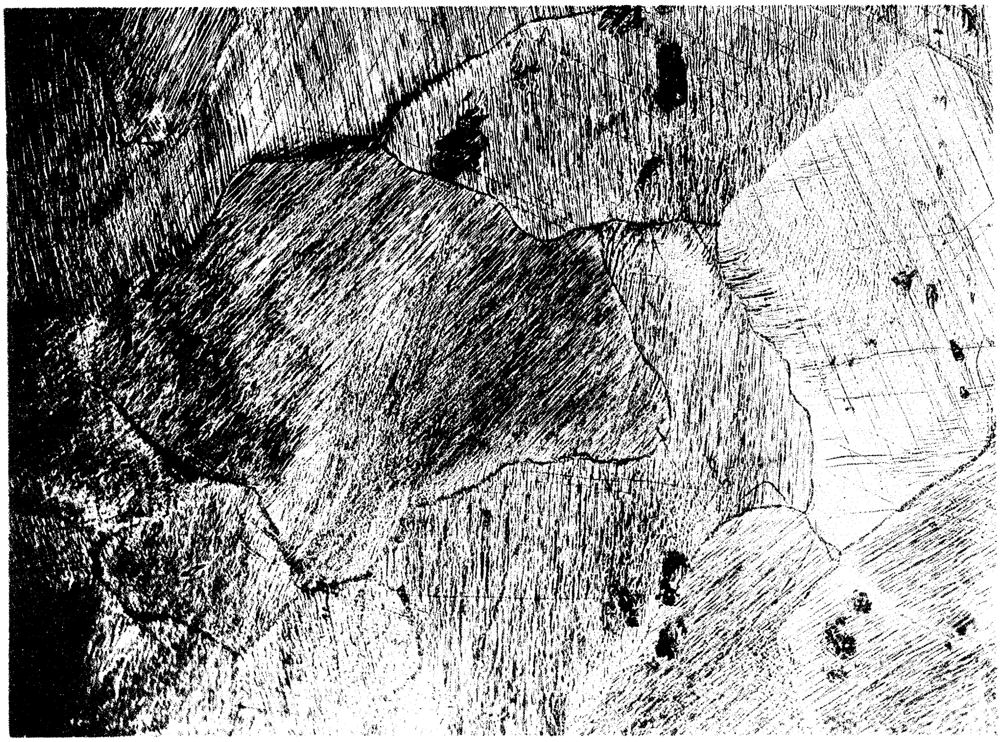


Fig. 18. LEAD × 100.

Fig. 19. LEAD × 100.

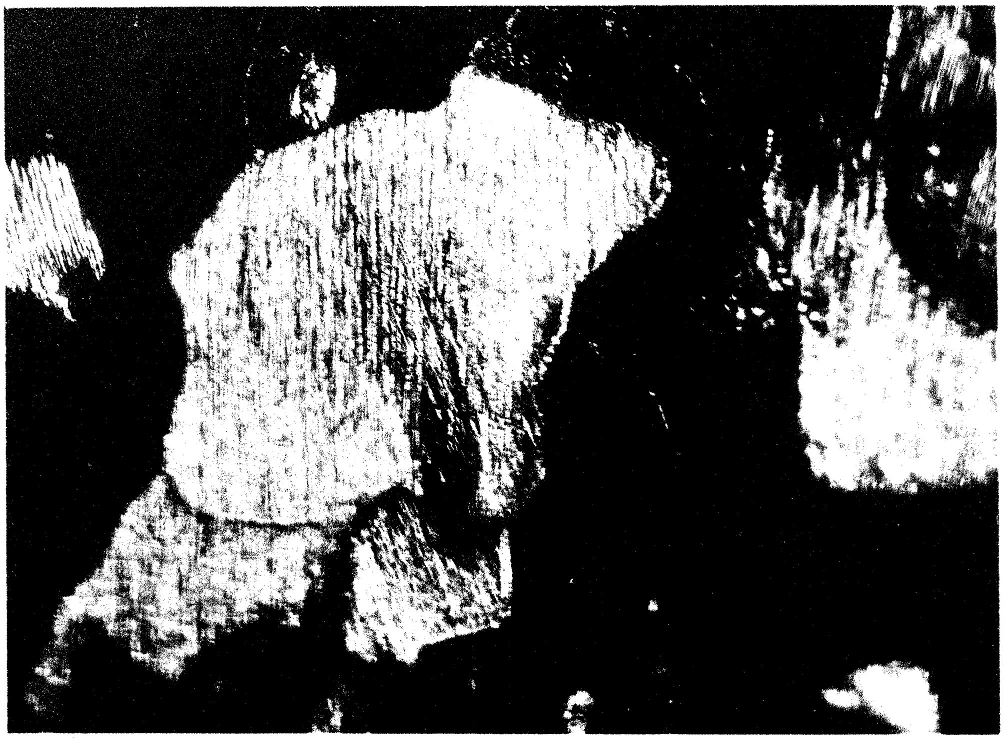


Fig 20. LEAD × 100.

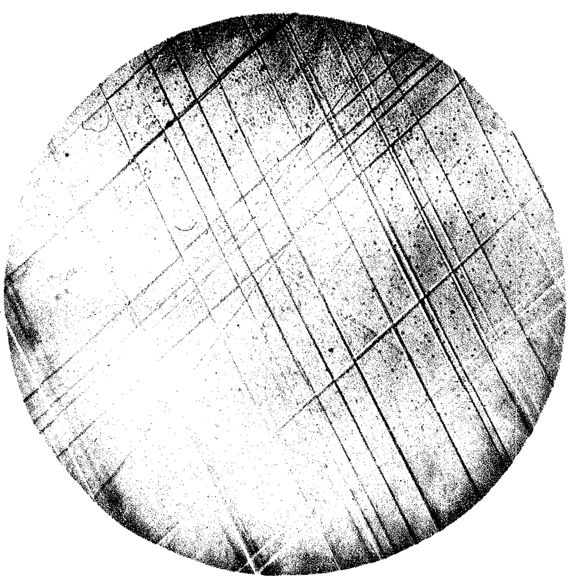


Fig. 23. LEAD × 600.

Fig. 24. LEAD × 1000.

Fig. 21. LEAD × 100.

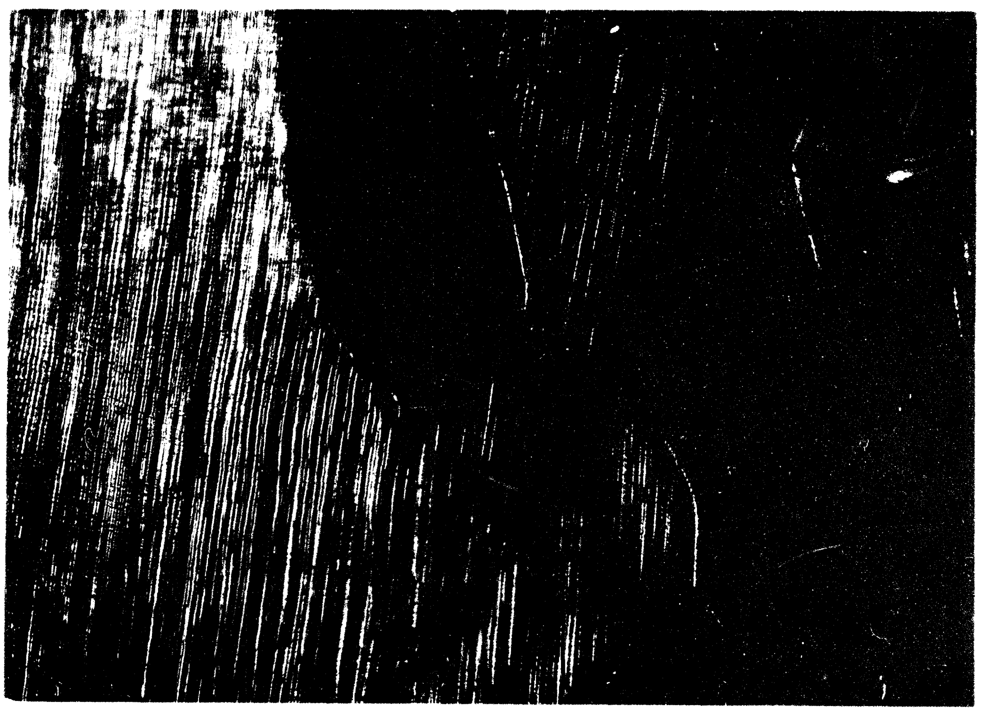


Fig. 22. LEAD × 100

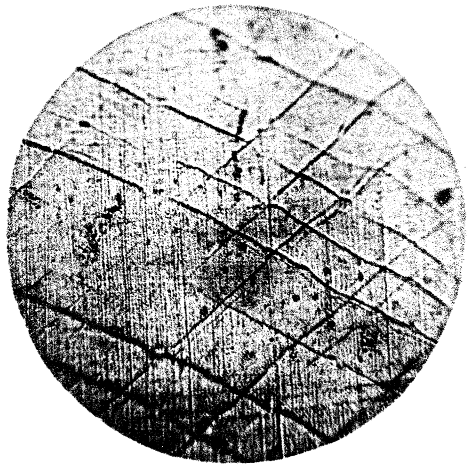


Fig. 25. SILVER × 750.

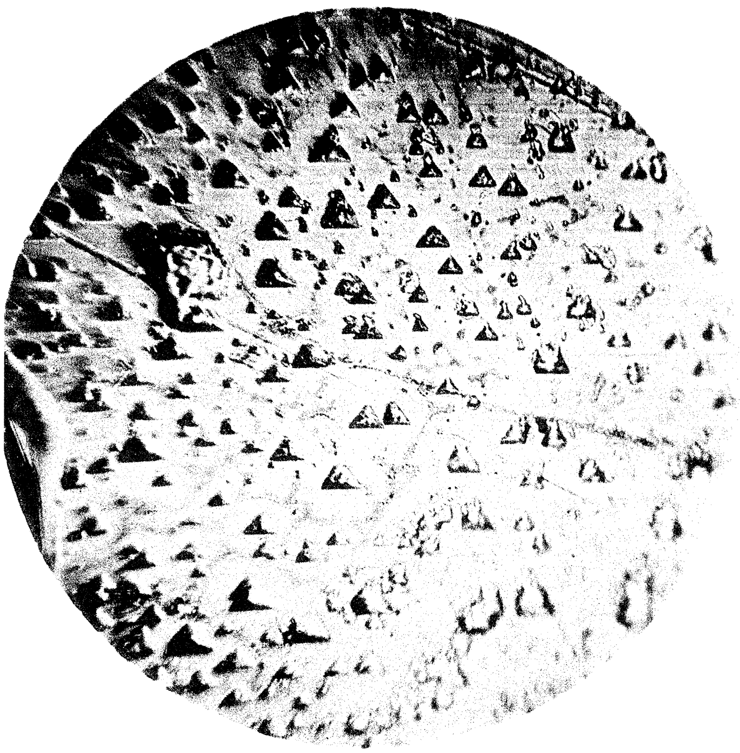


Fig. 26. CADMIUM × 1000.

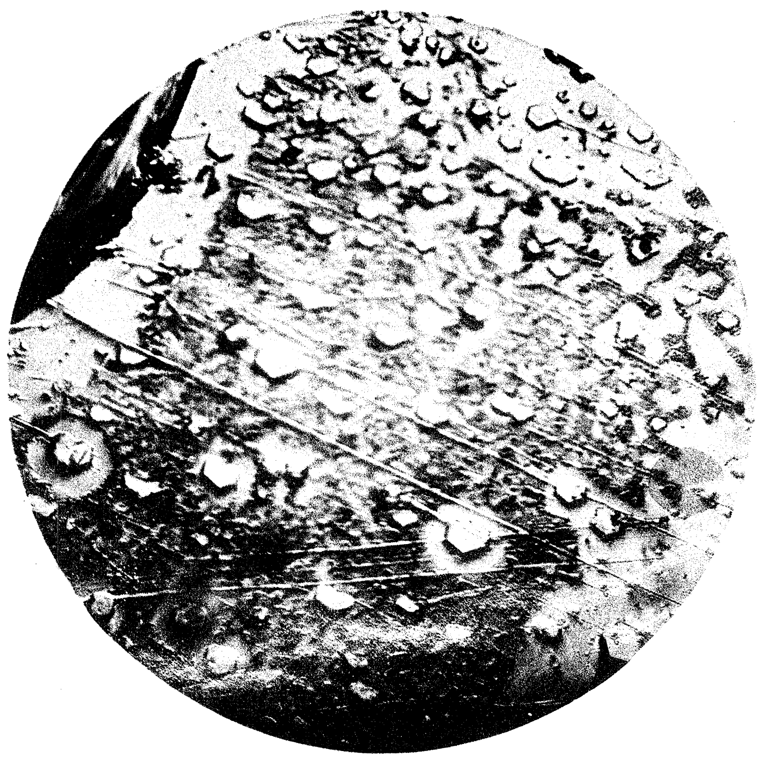


Fig. 27. CADMIUM × 1000.

Fig. 28. CADMIUM × 1000.

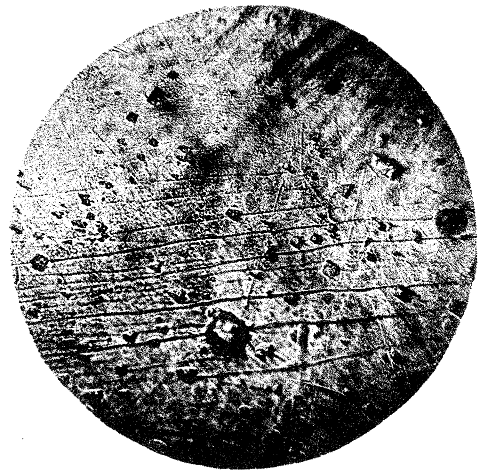


Fig. 29. IRON × 750.

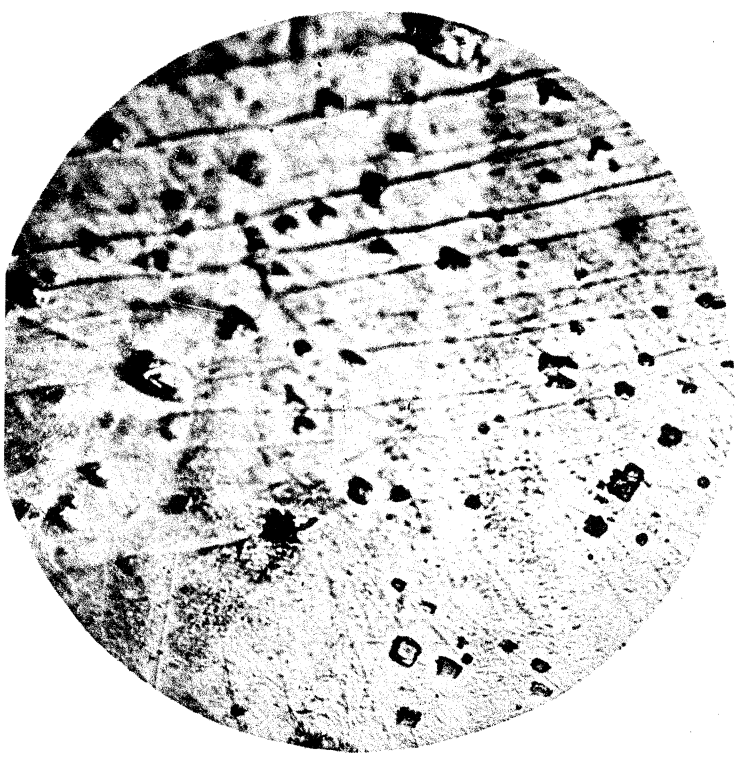


Fig. 30. IRON × 1000.

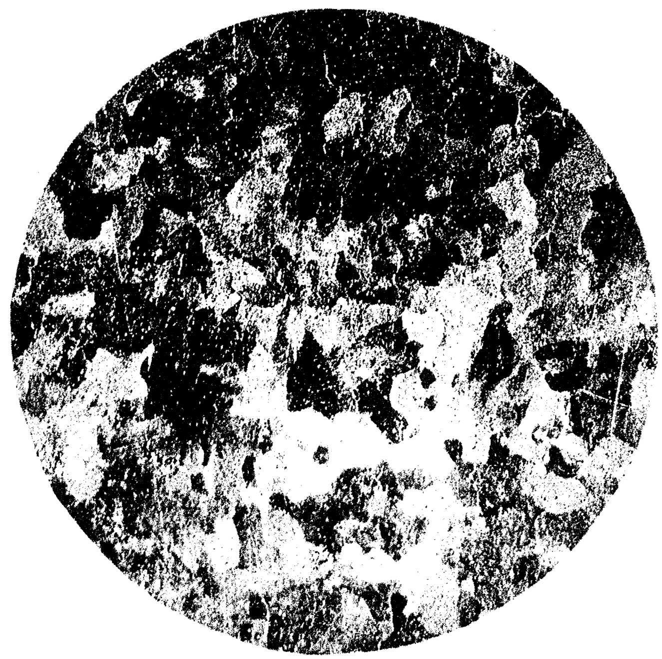


Fig. 31. IRON × 45.

Fig. 32. IRON × 200.

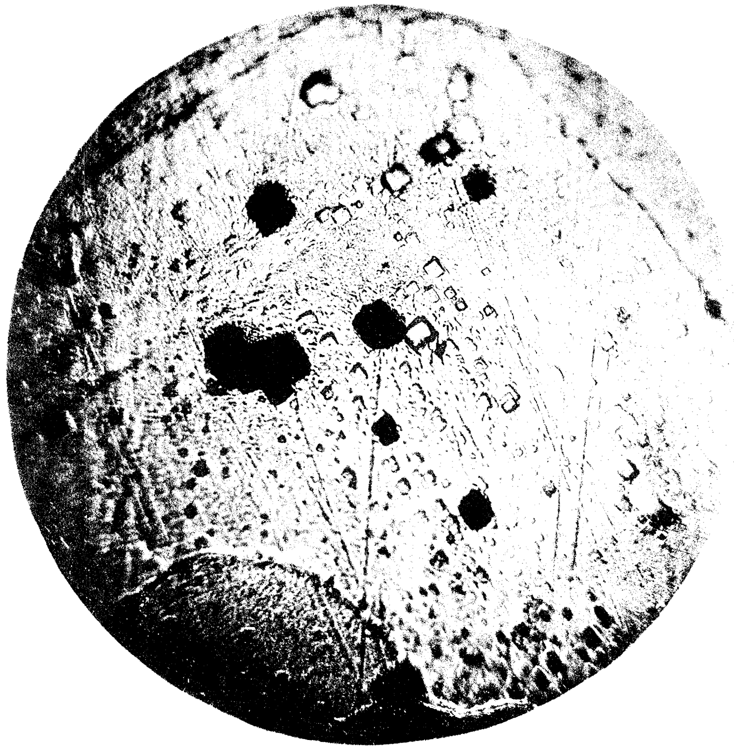


Fig. 33. IRON × 800.

Fig. 34. COPPER × 1000.

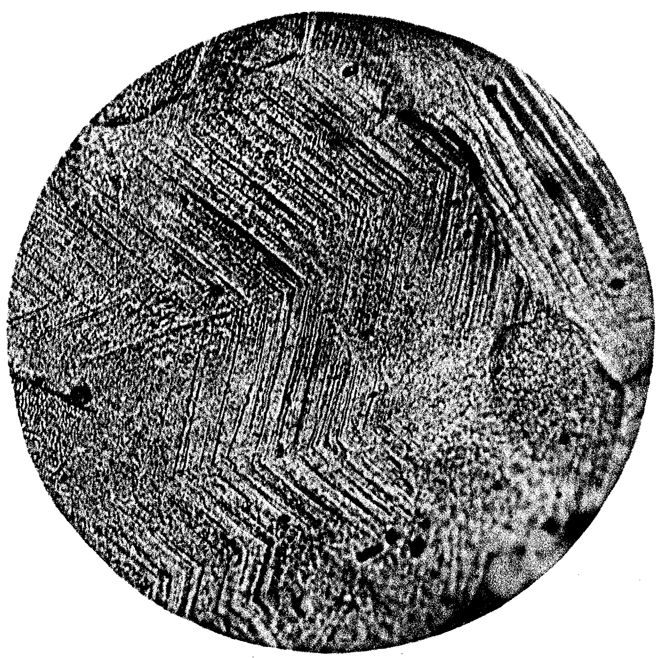


Fig. 35. COPPER × 1000.

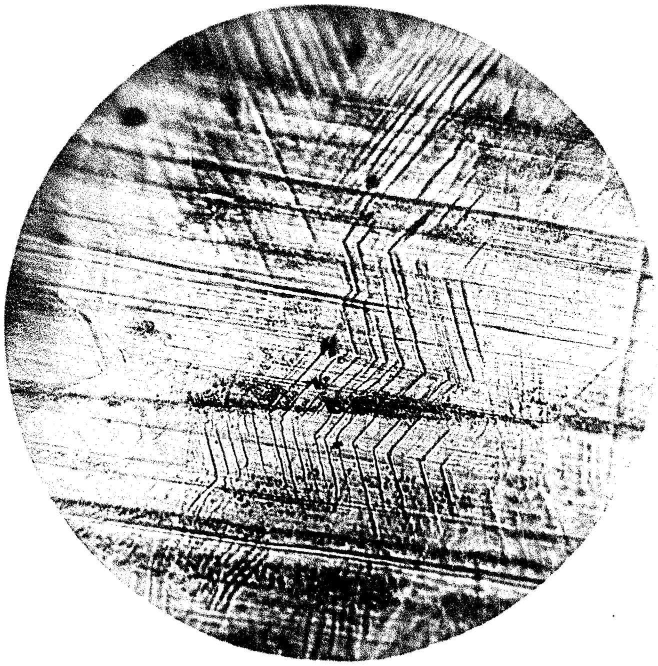


Fig. 36. COPPER × 1000.

Fig. 37. GOLD × 200.

Fig. 38. GOLD × 45.

Fig. 39. COPPER × 1000.

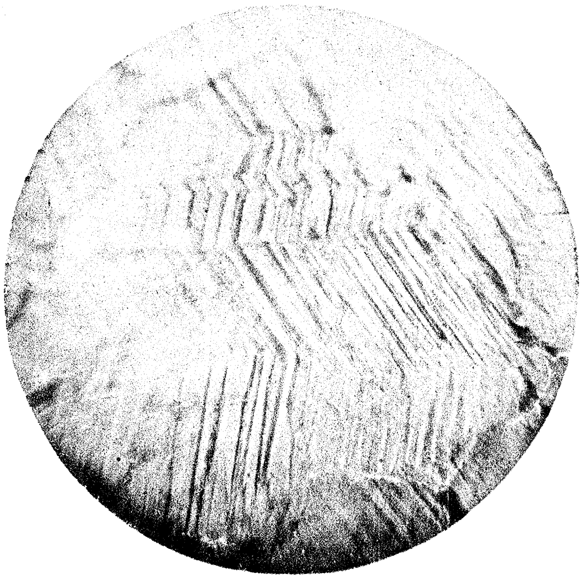


Fig. 40. LEAD × 1000.

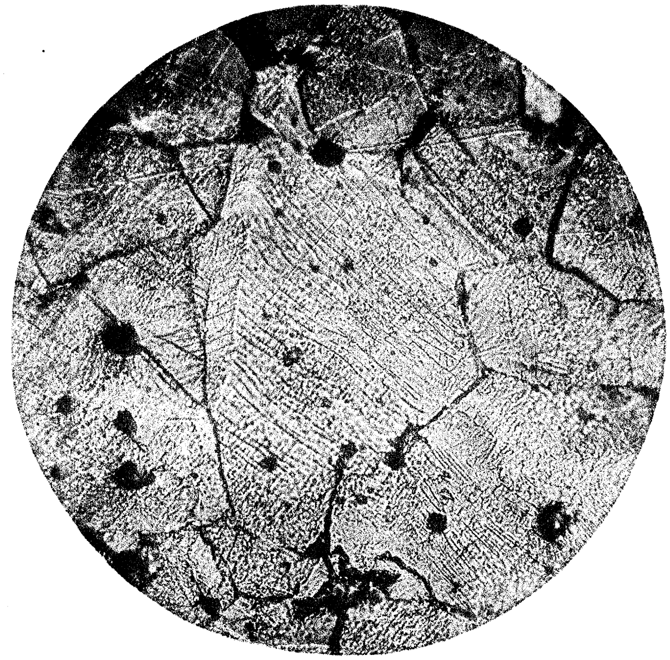


Fig. 41. NICKEL × 1000.

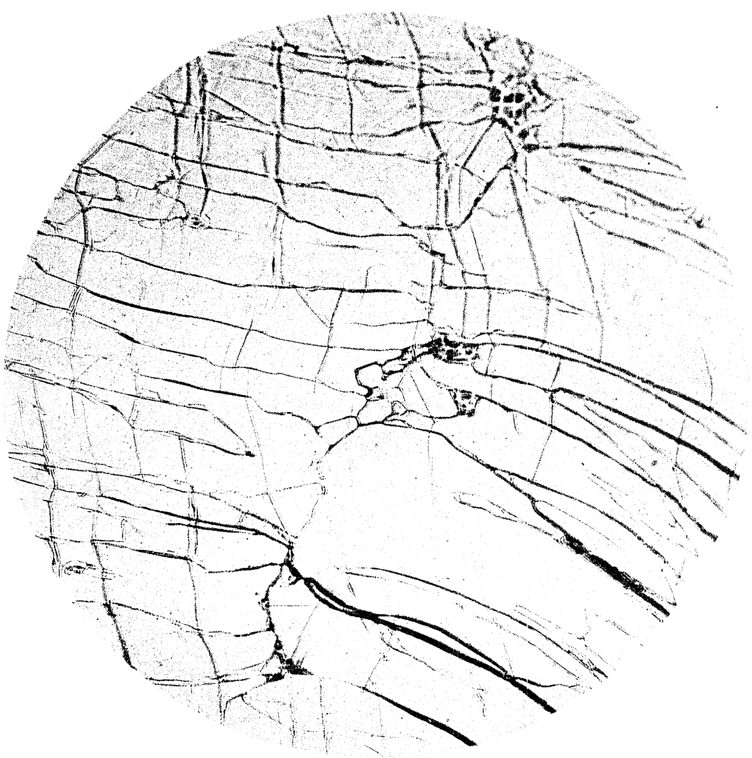


Fig. 42. CADMIUM × 100.

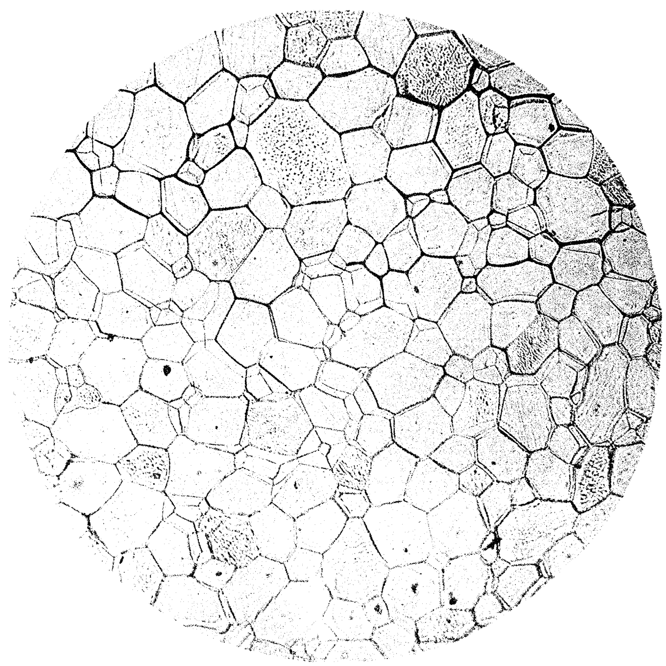


Fig. 43. CADMIUM × 100.

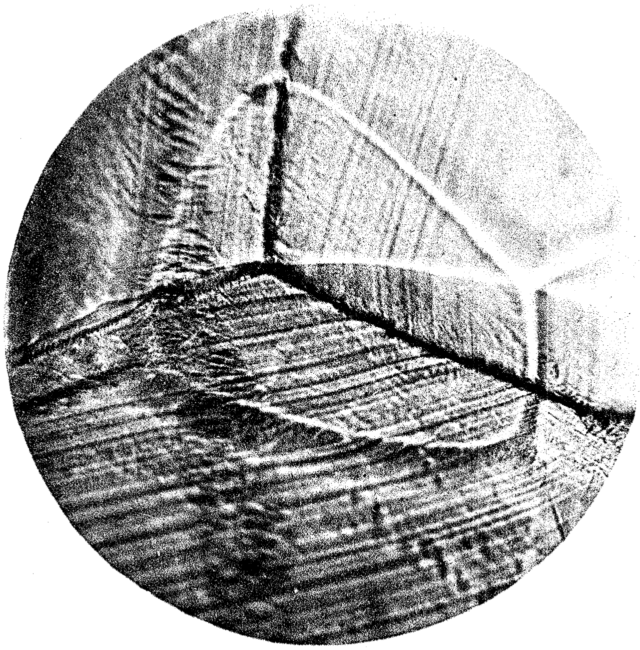


Fig. 44. CADMIUM × 1000.

Fig. 45. MILD STEEL × 1000.

Fig. 46. LEAD-TIN EUTECTIC × 750.

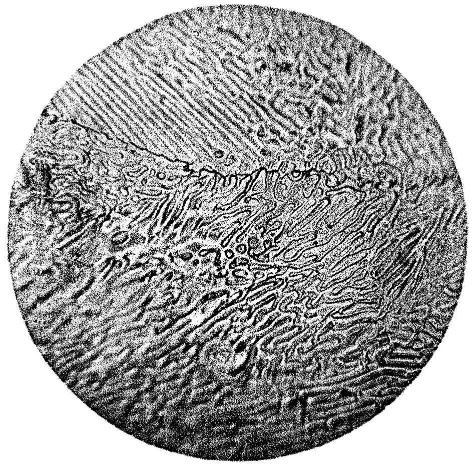


Fig. 47. LEAD-TIN EUTECTIC × 750.

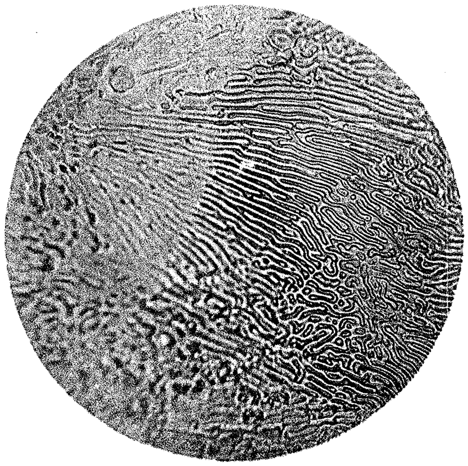


Fig. 48. Lead-Tin Eutectic × 750.

Fig. 49. Lead-Bismuth Eutectic × 1000.

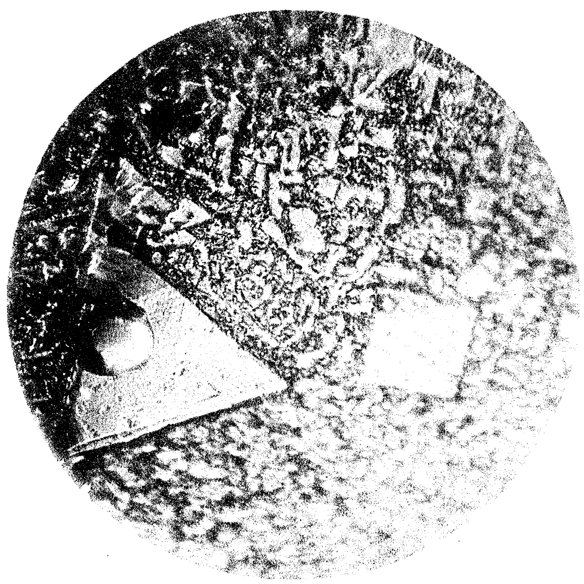


Fig. 50. Lead-Bismuth Alloy × 1000.

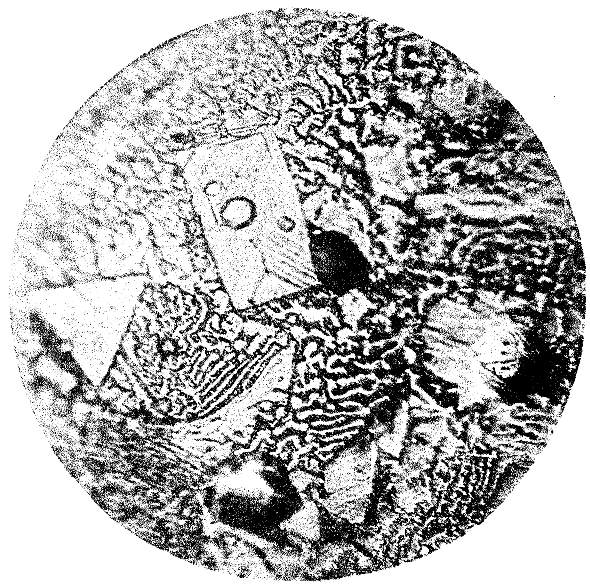


Fig. 51. Lead-Bismuth Alloy × 1000.

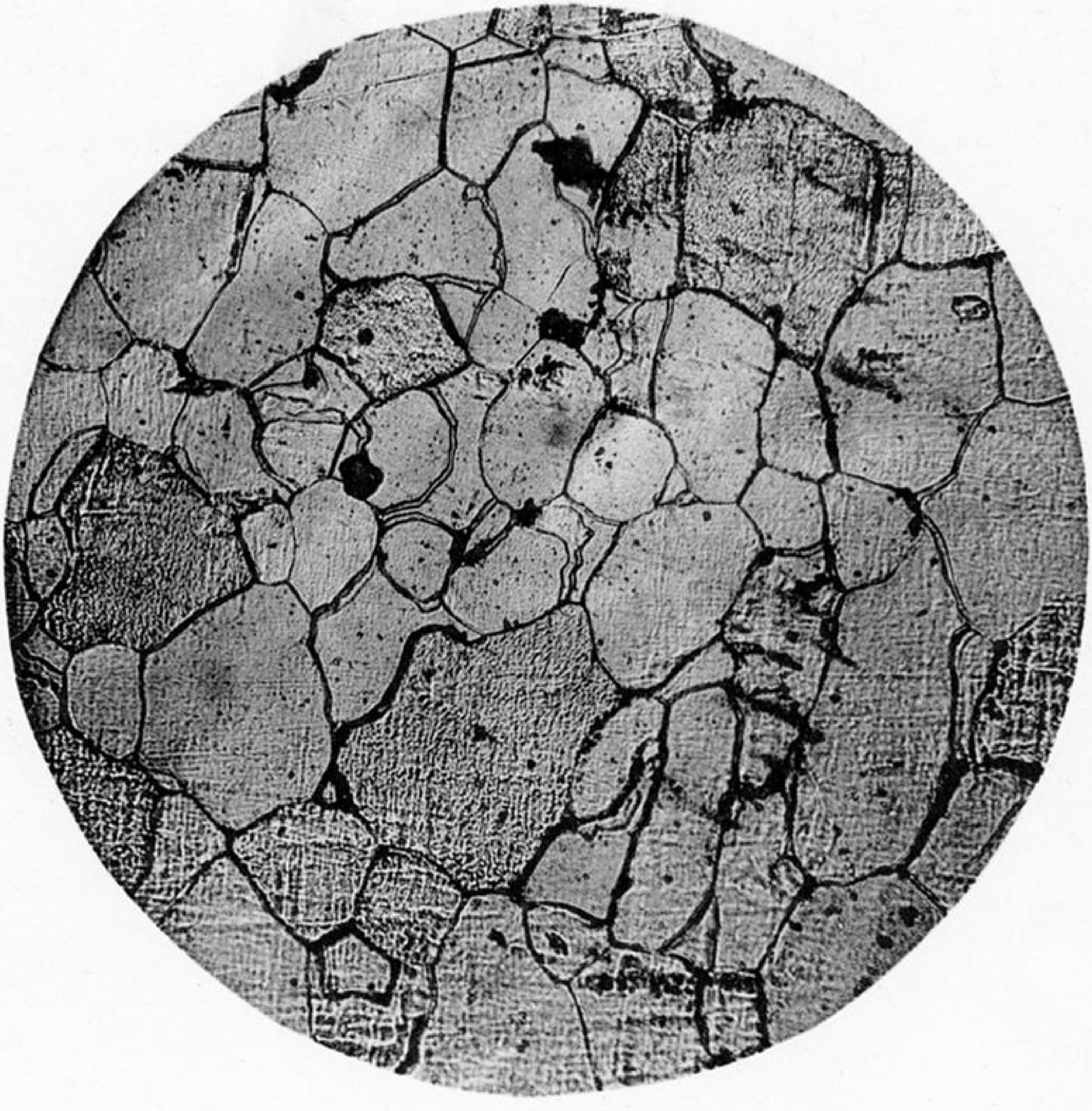


Fig. 2. IRON × 200.

Fig. 3. Bismuth × $\frac{2}{5}$.

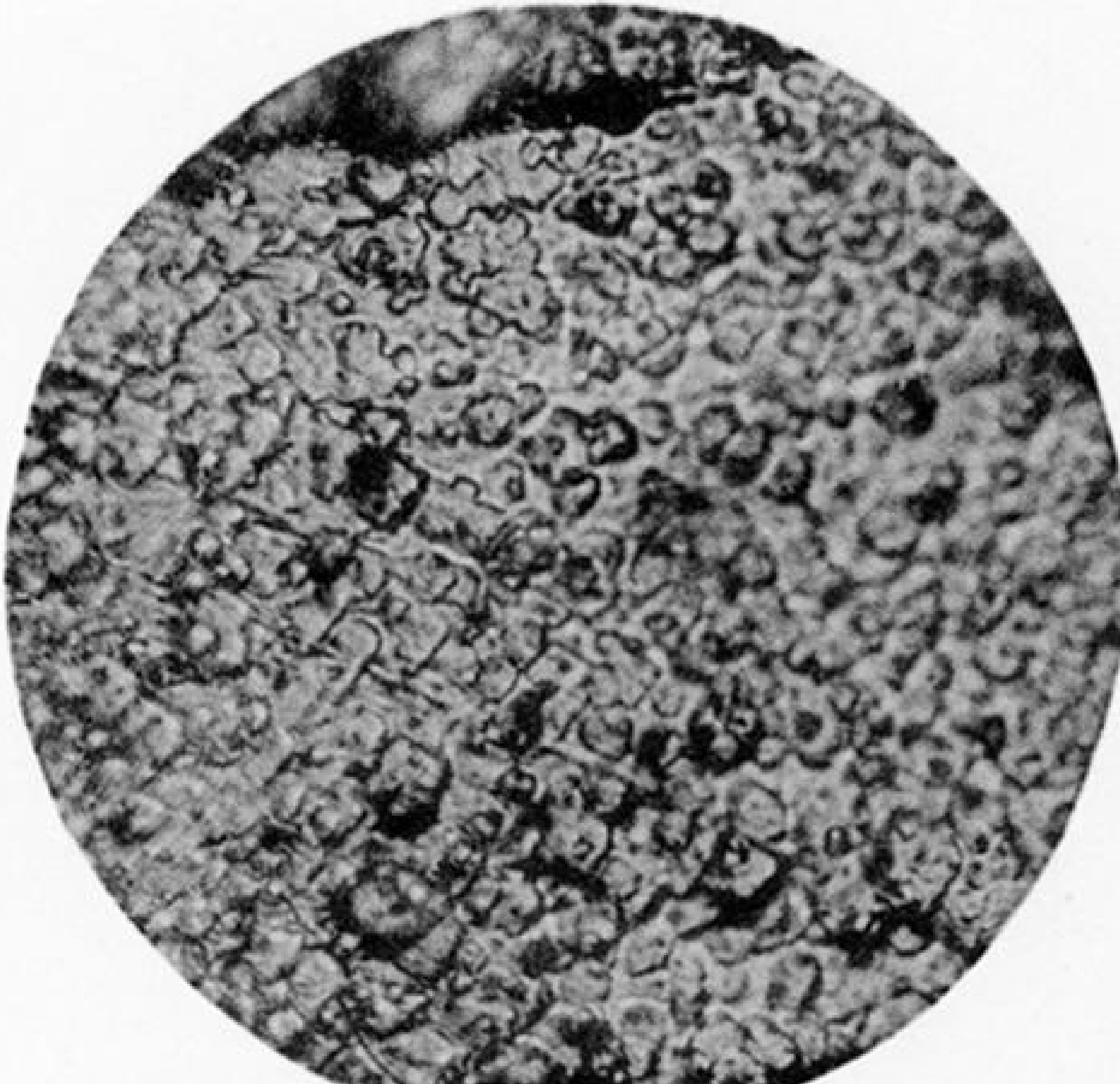


Fig. 4 Iron × 1500.

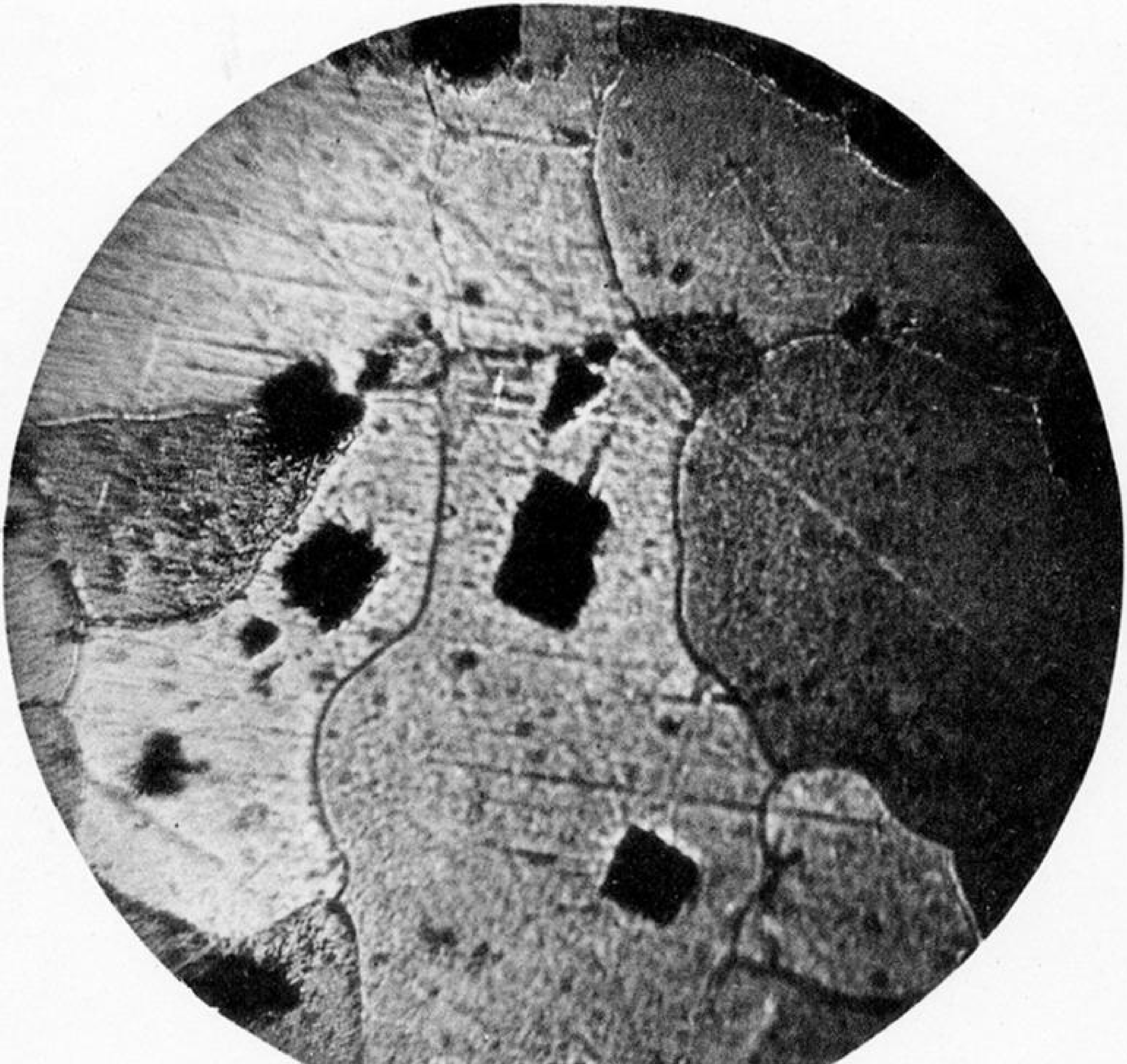


Fig. 5. Iron × 1000.

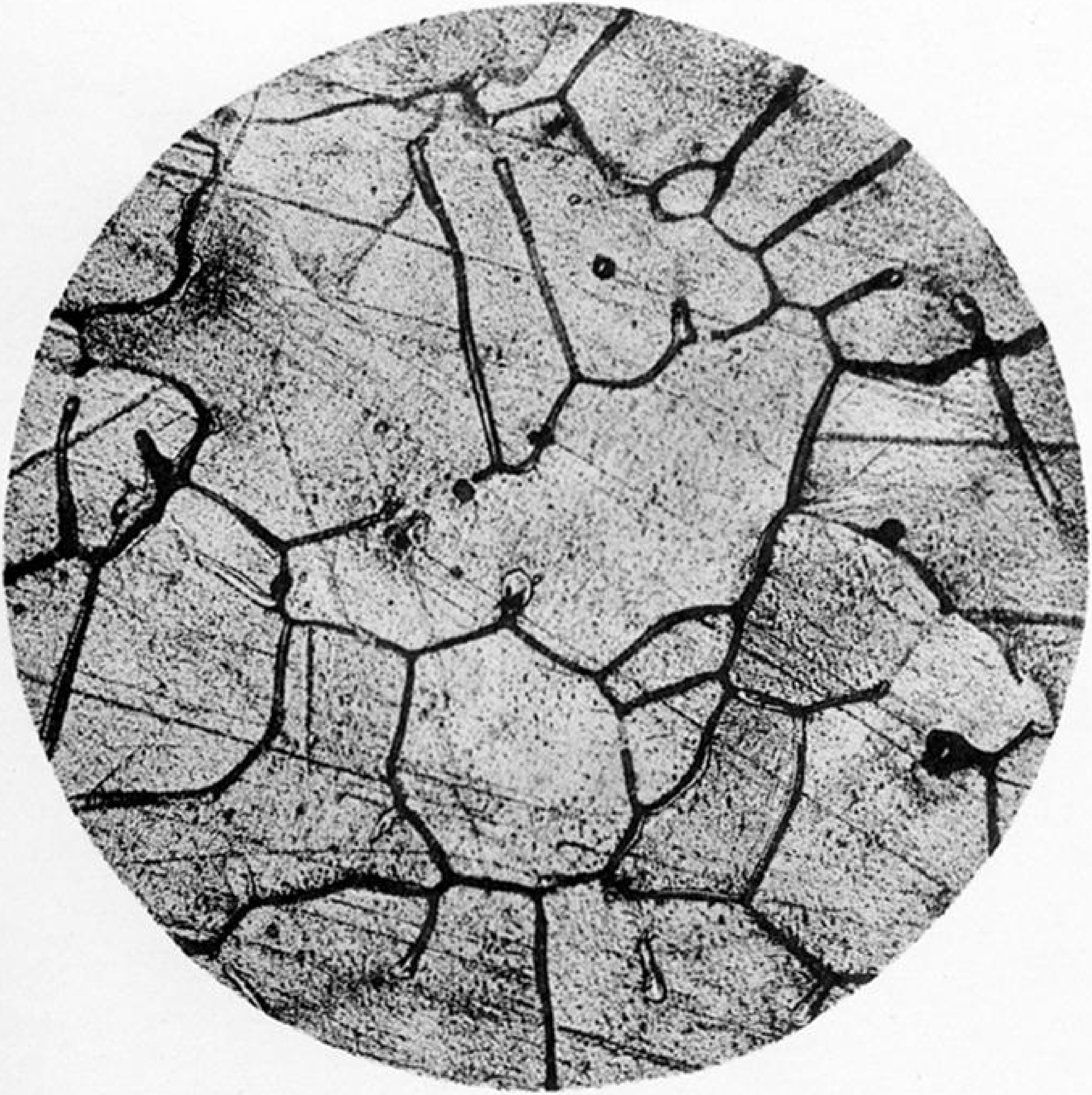


Fig. 6. Cadmium × 100.

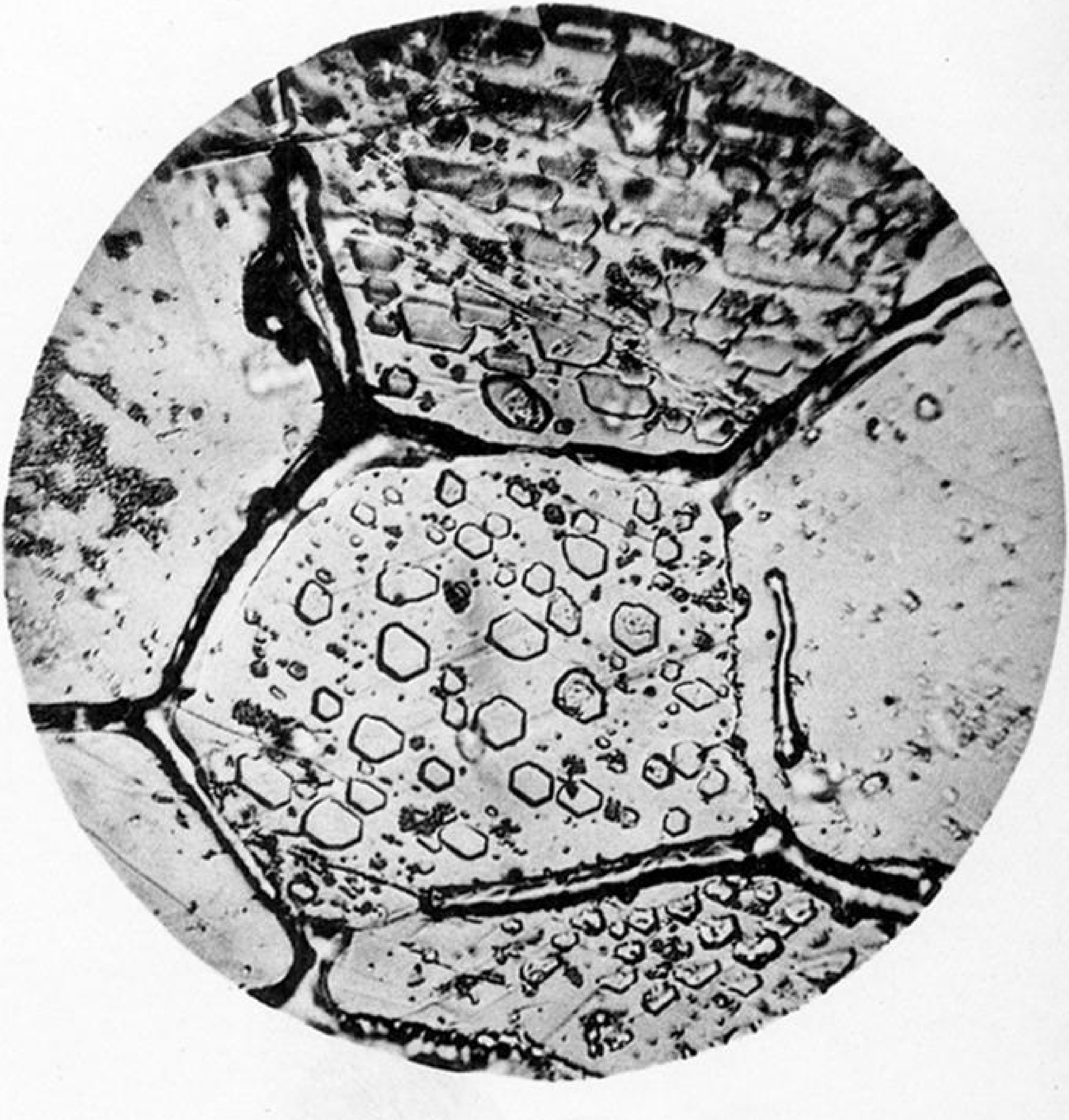


Fig. 7. Cadmium × 1000

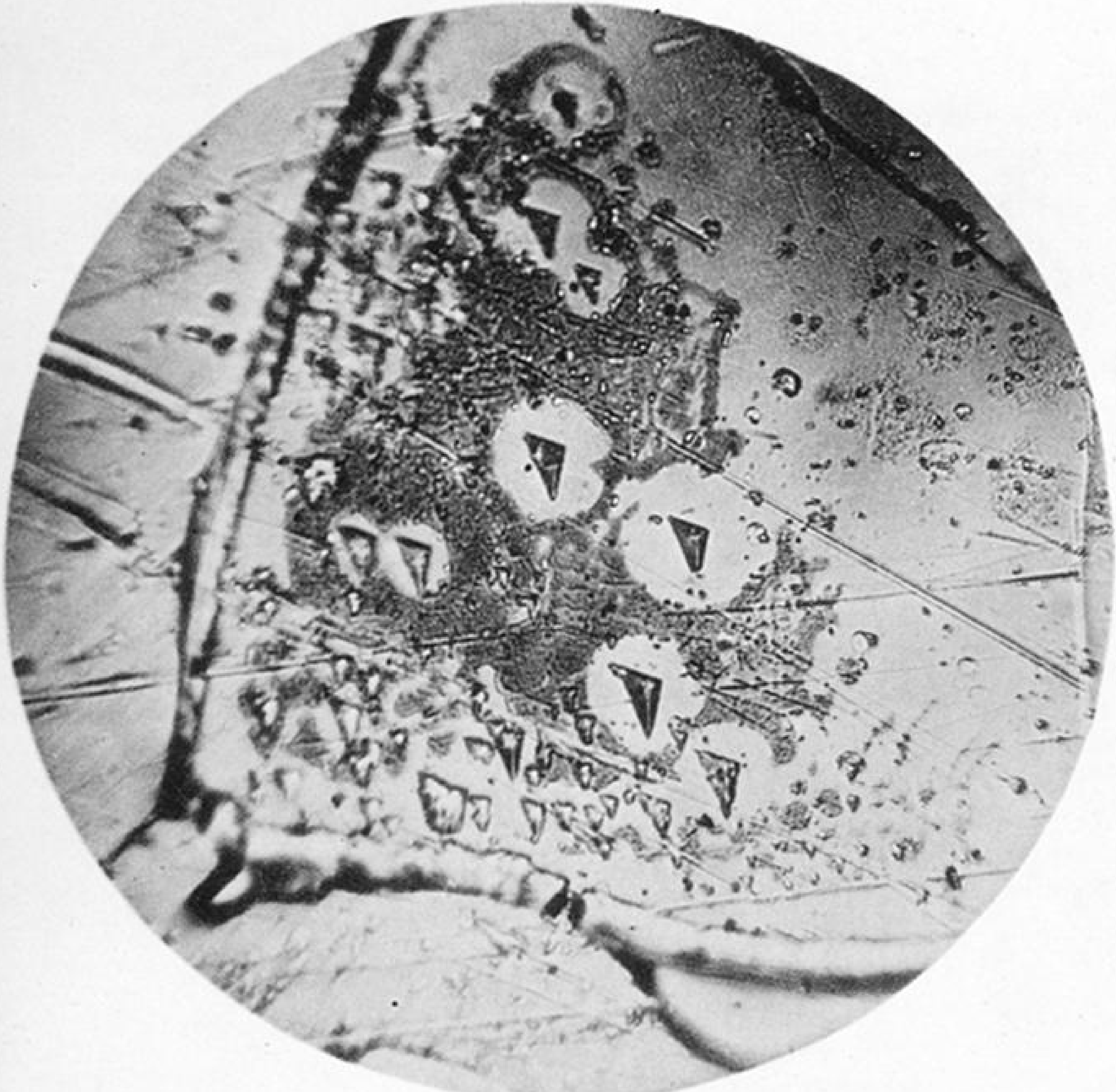


Fig. 8. CADMIUM × 1000.

Fig. 9. Cadmium × 4200.

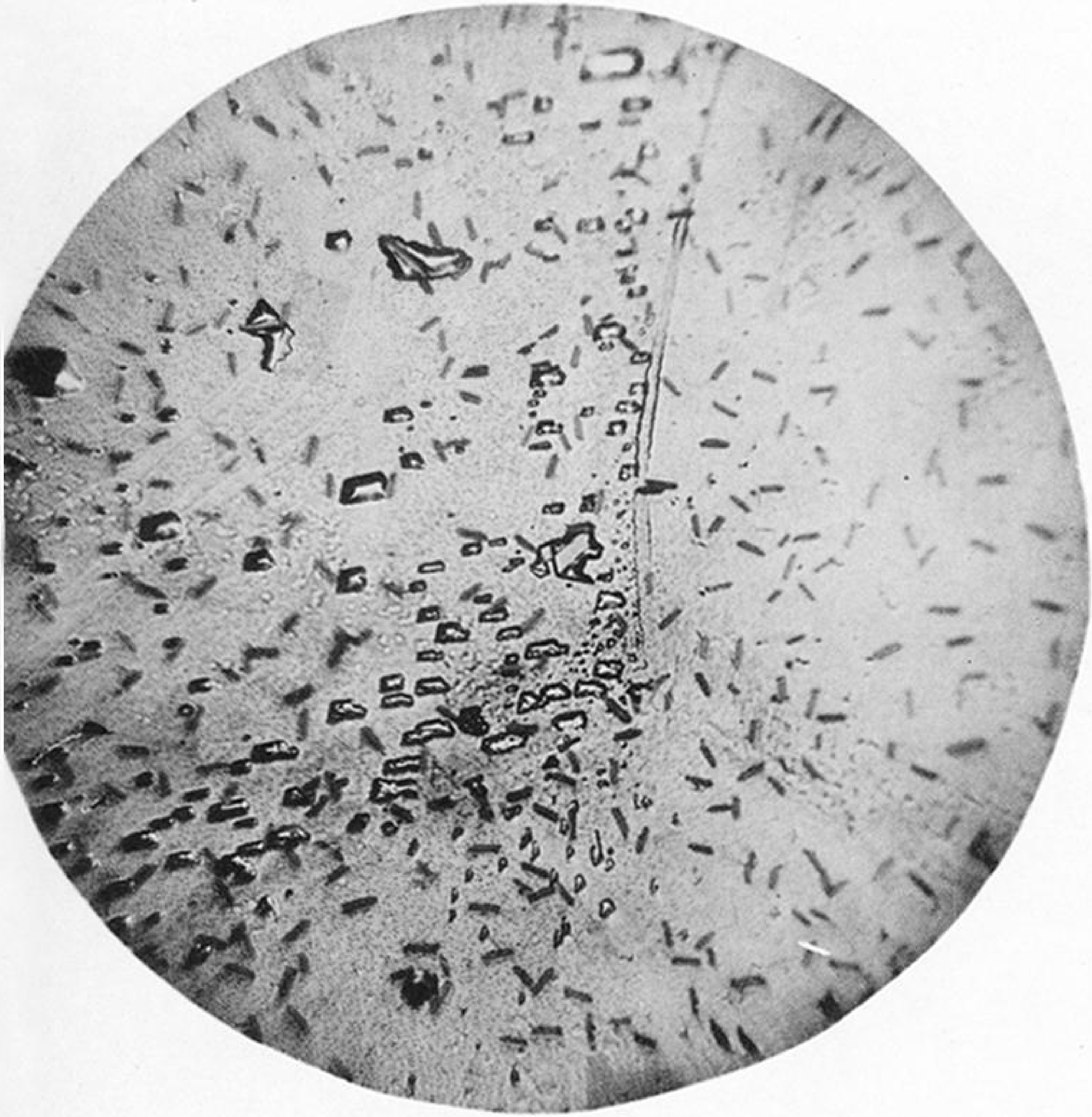


Fig. 10. Tin × 1000.

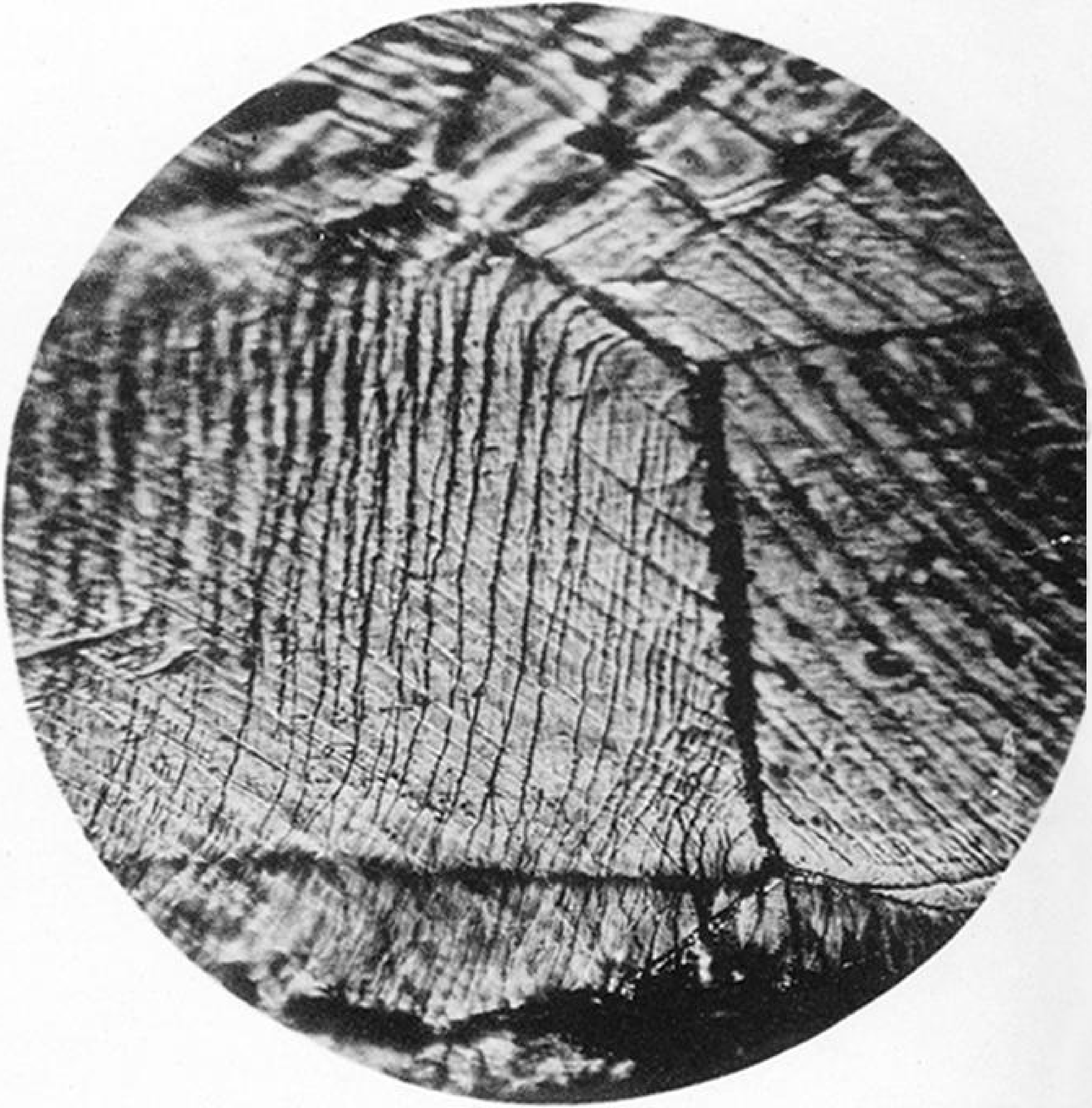


Fig. 12. Iron × 400

Fig. 13. Iron × 200.

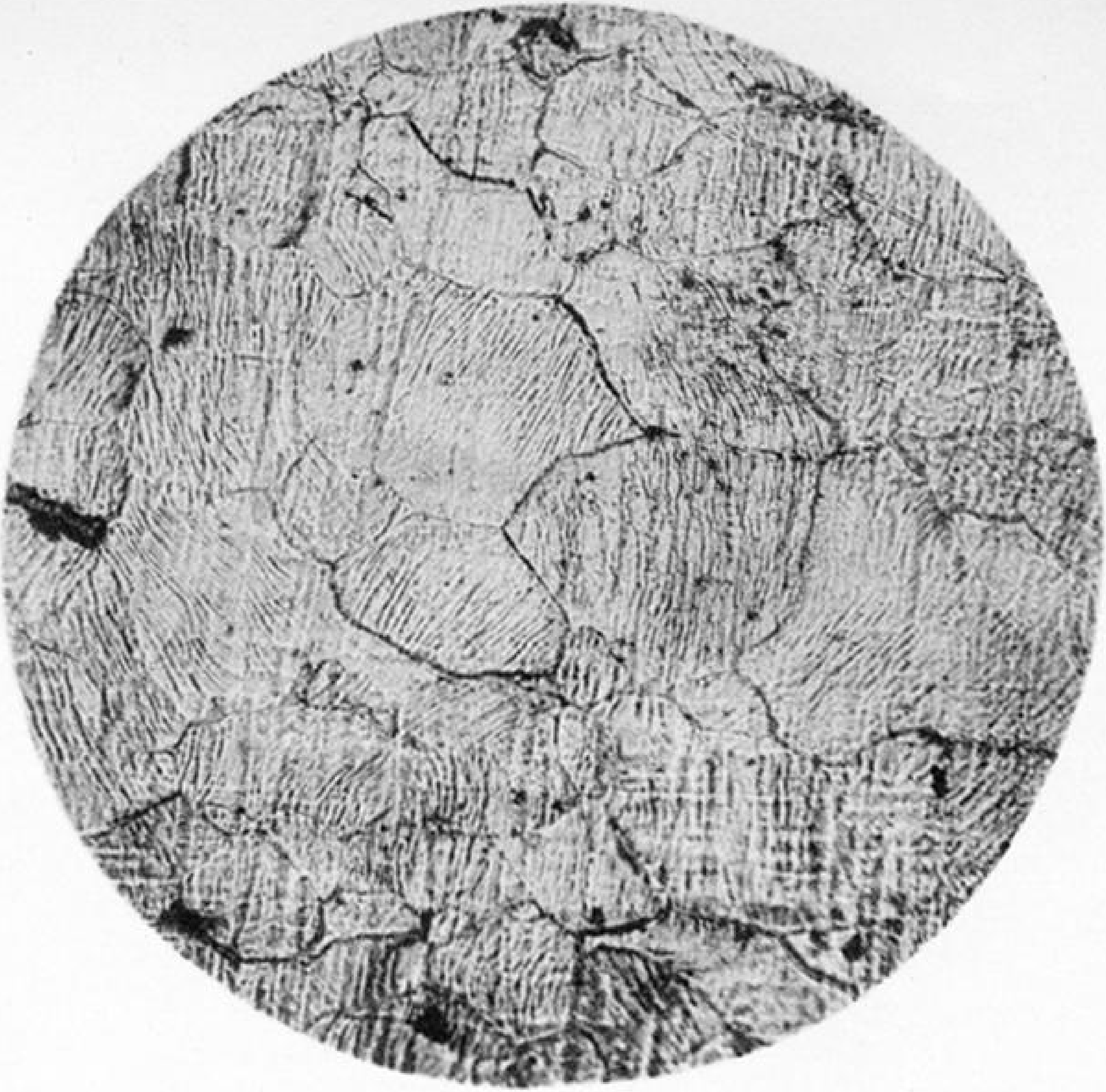


Fig. 14. Iron × 200.

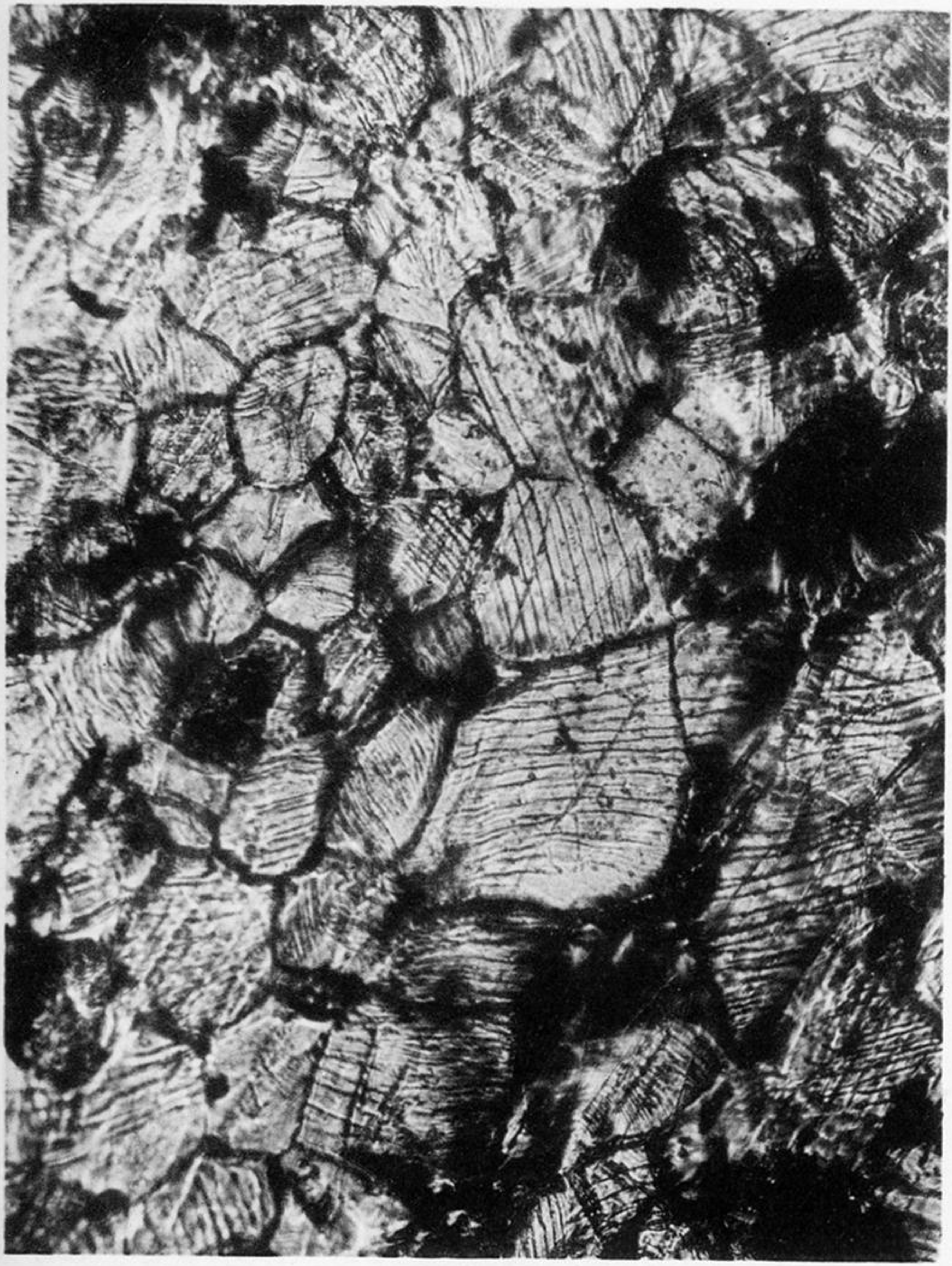


Fig. 16. Iron × 300.

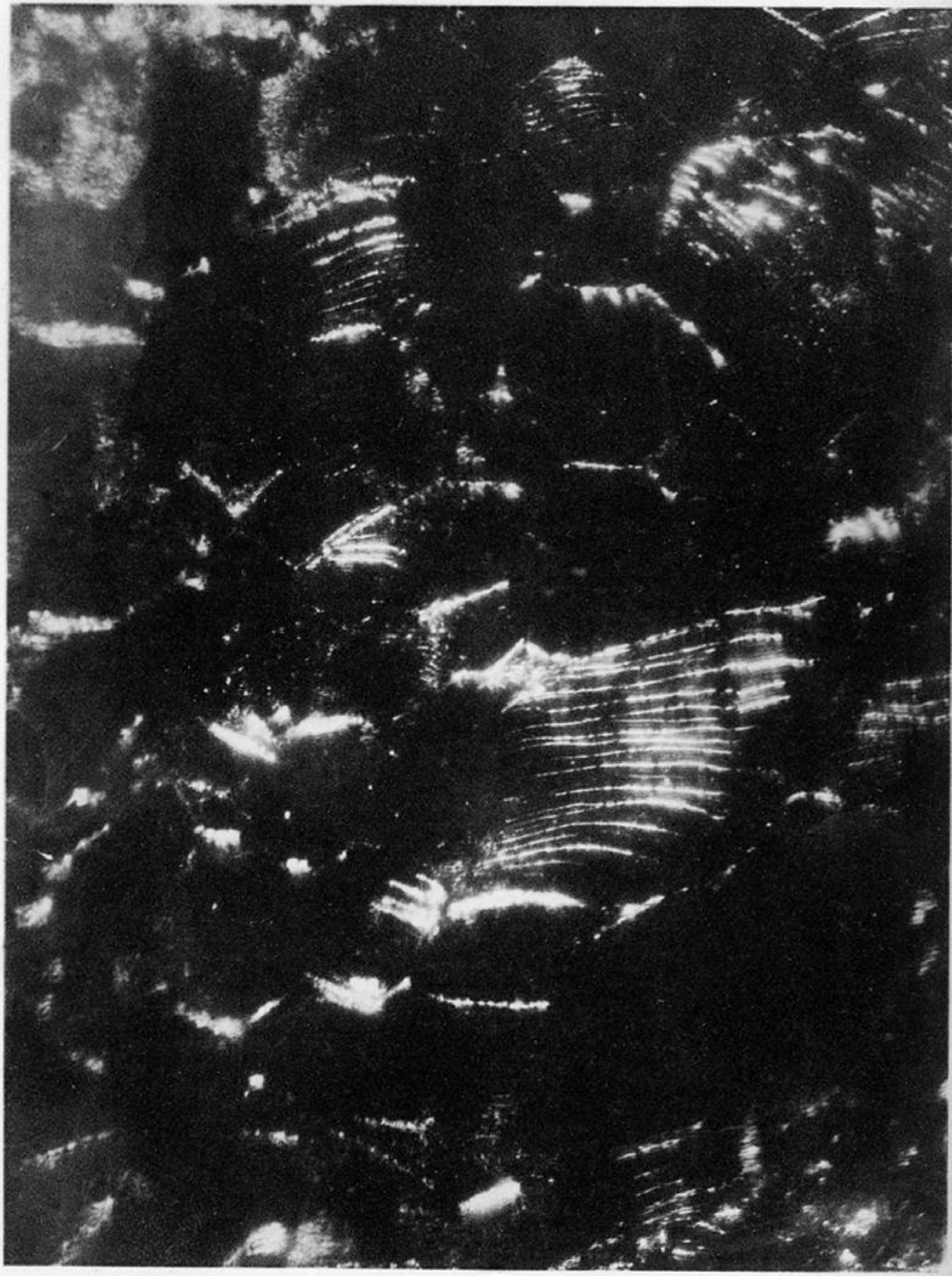


Fig. 17. Iron × 300.

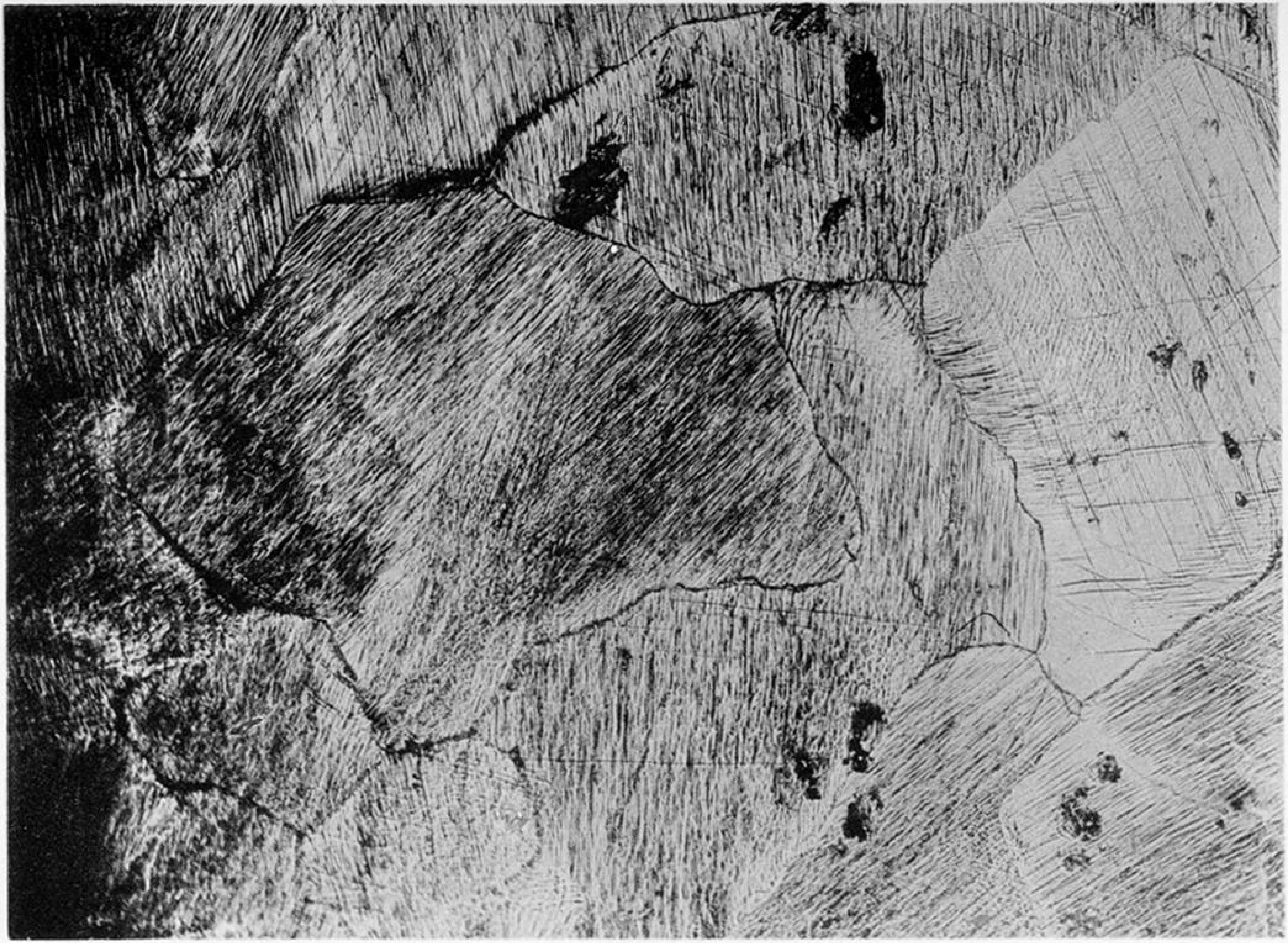


Fig. 18. Lead × 100.

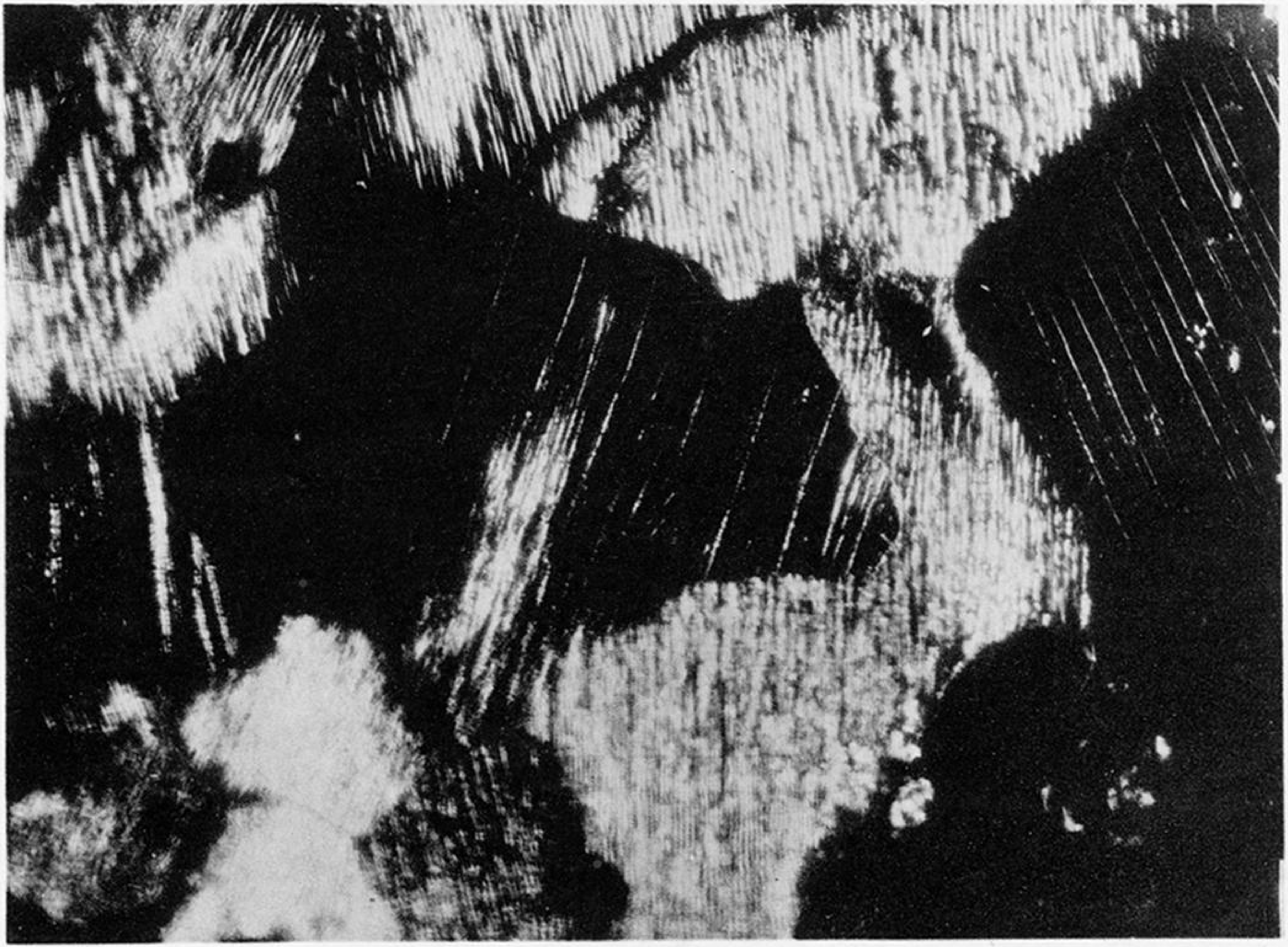


Fig. 19. Lead × 100.

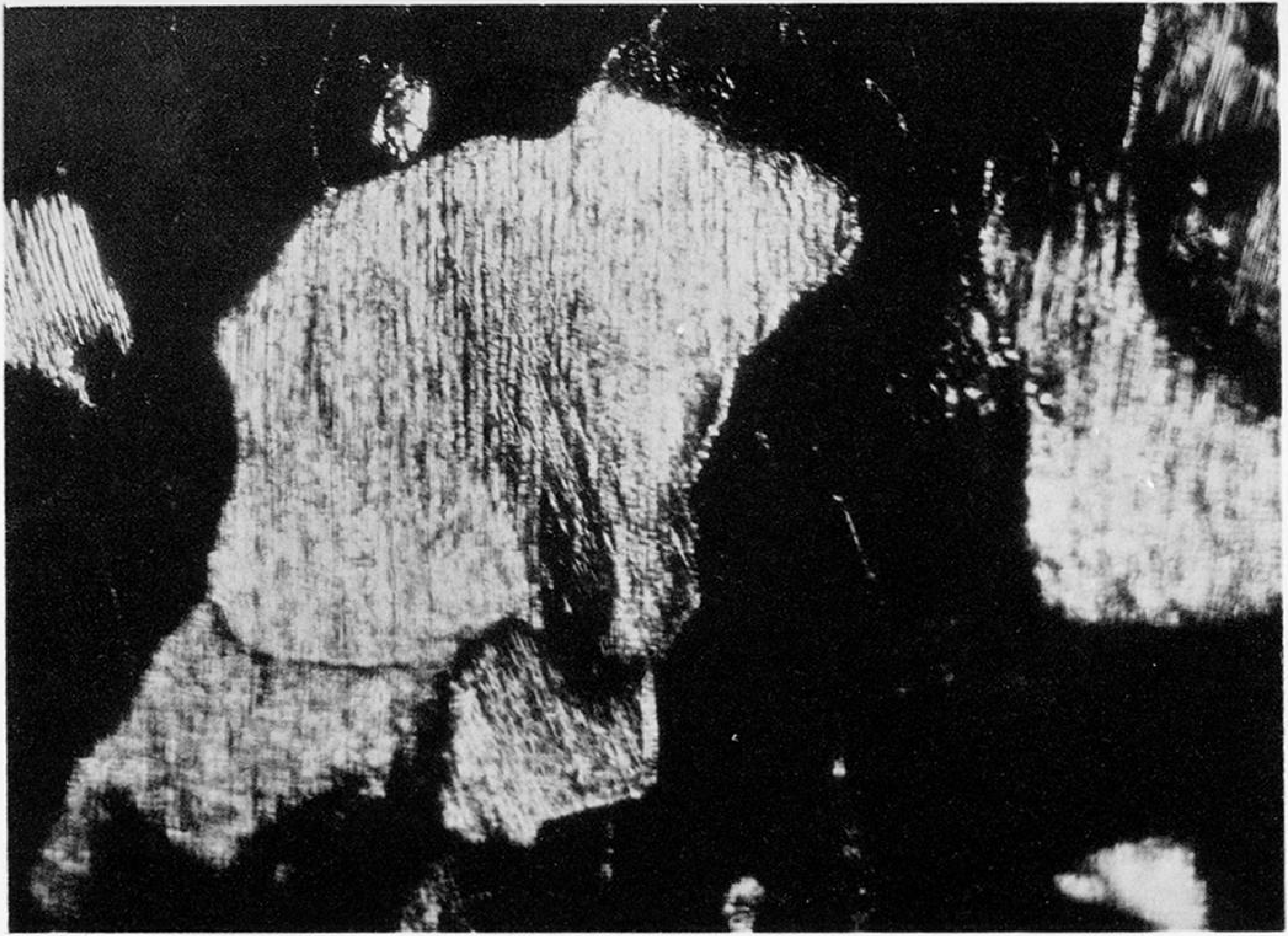


Fig 20. LEAD × 100.

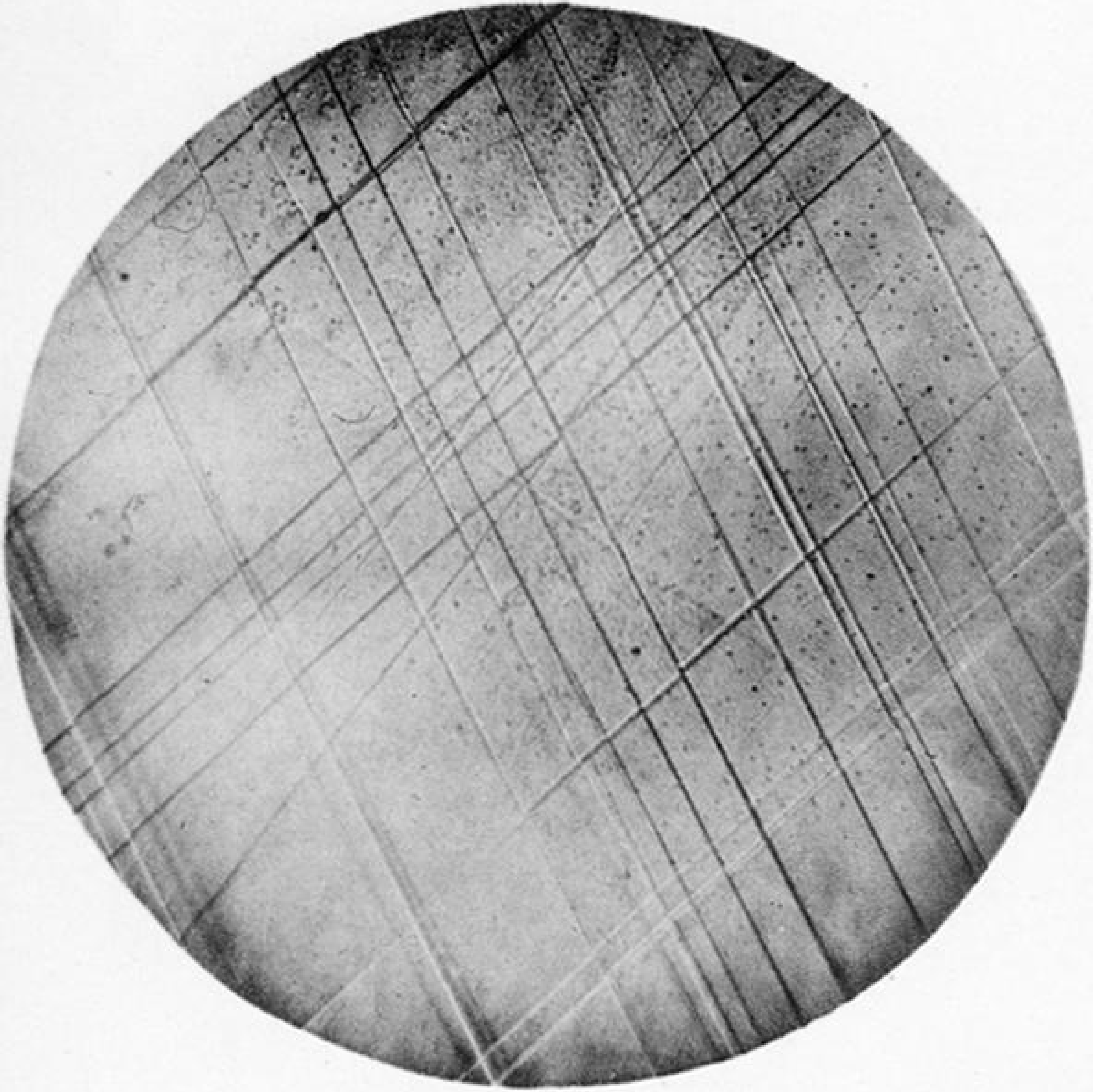


Fig. 23. Lead × 600.

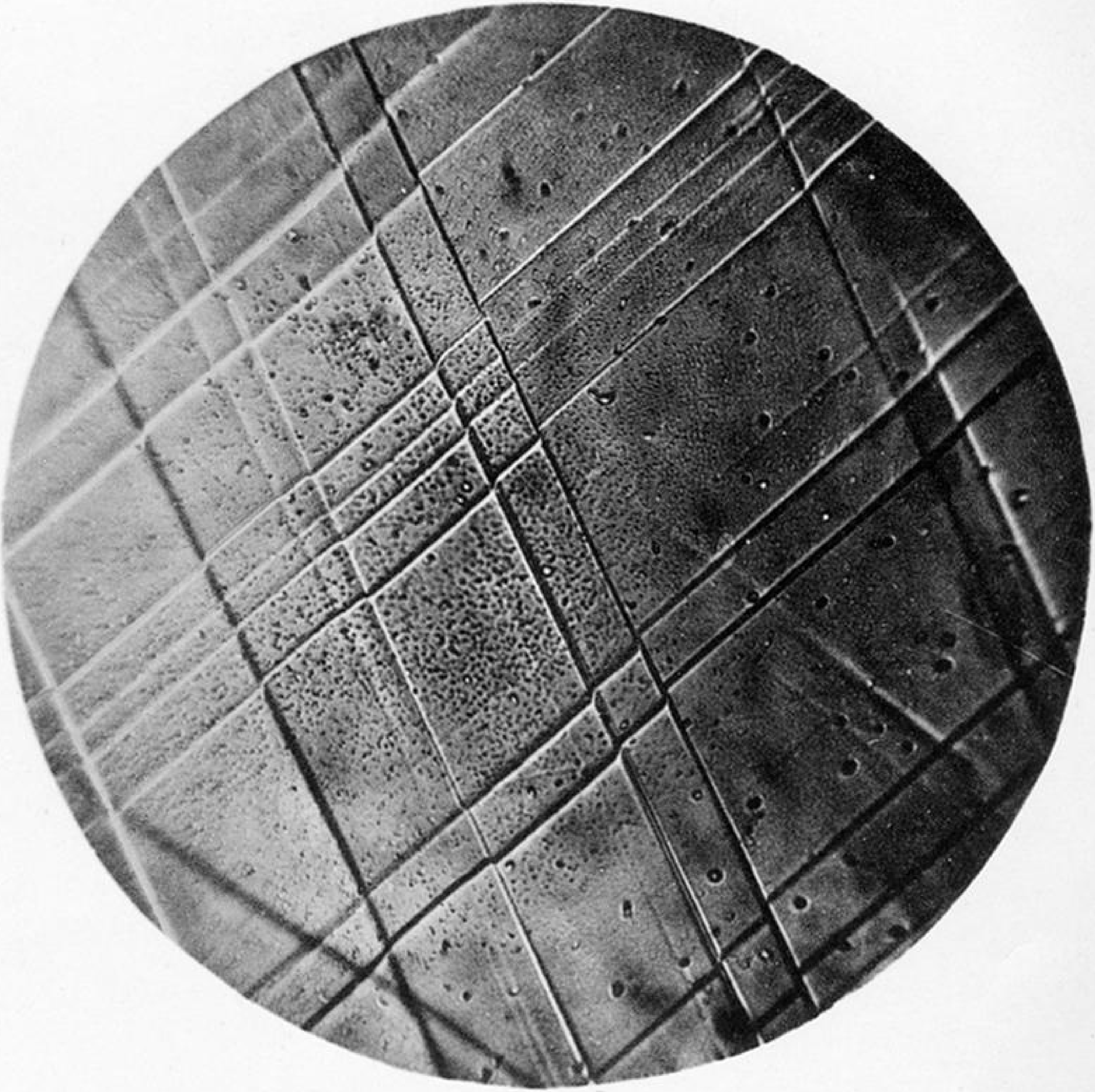


Fig. 24. LEAD × 1000.

Fig. 21. LEAD × 100.

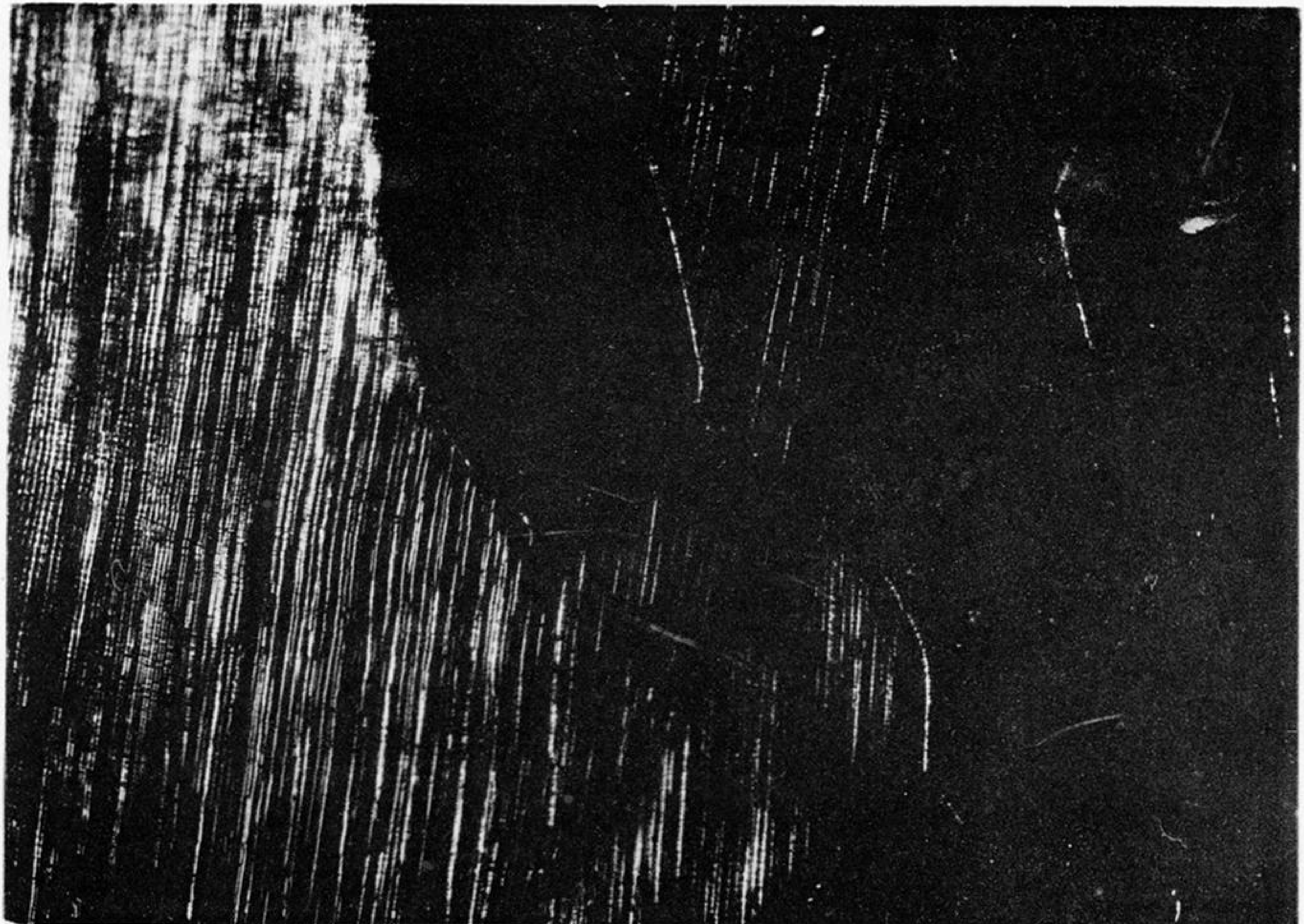


Fig. 22. LEAD × 100

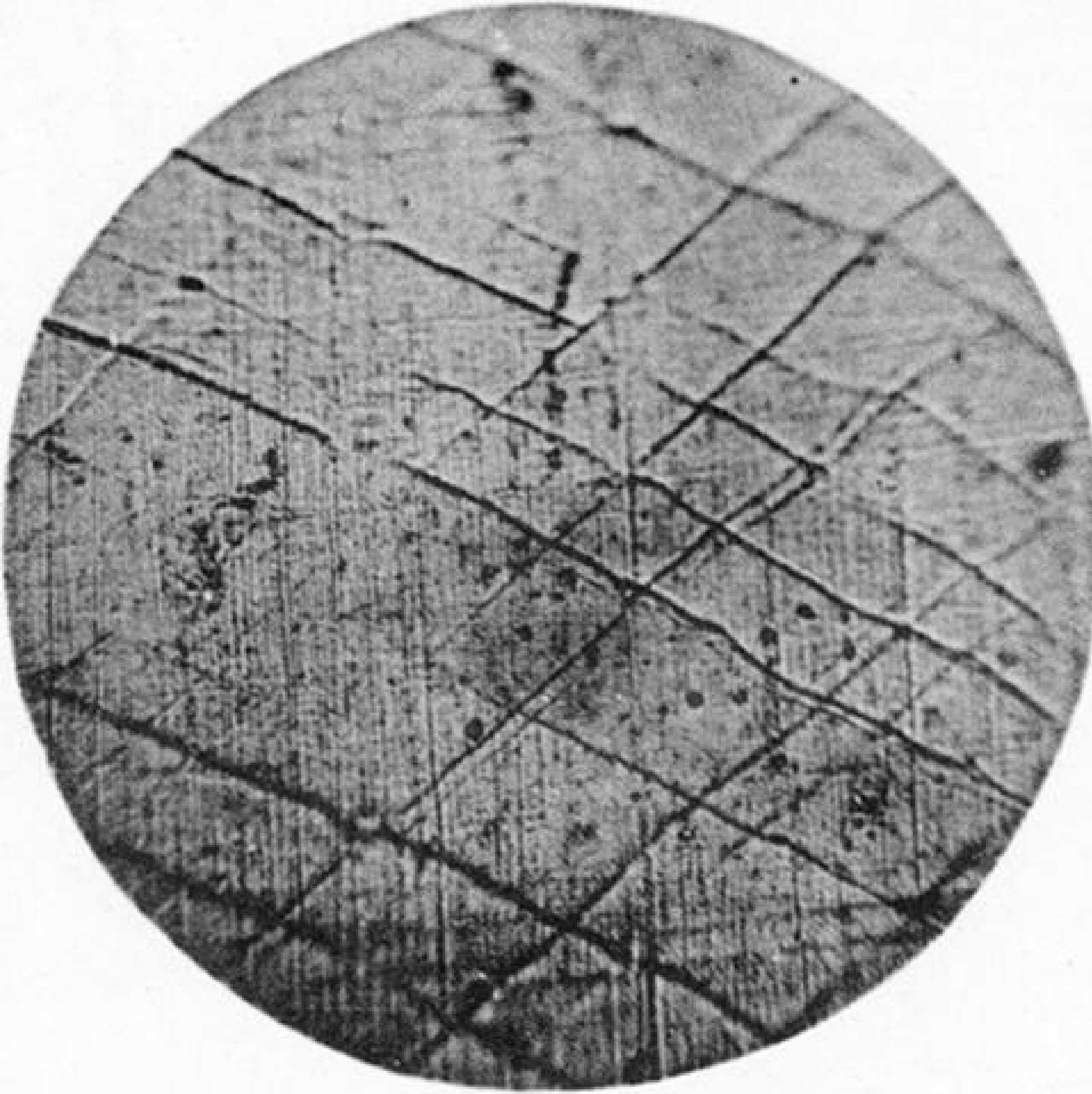


Fig. 25. Silver × 750.

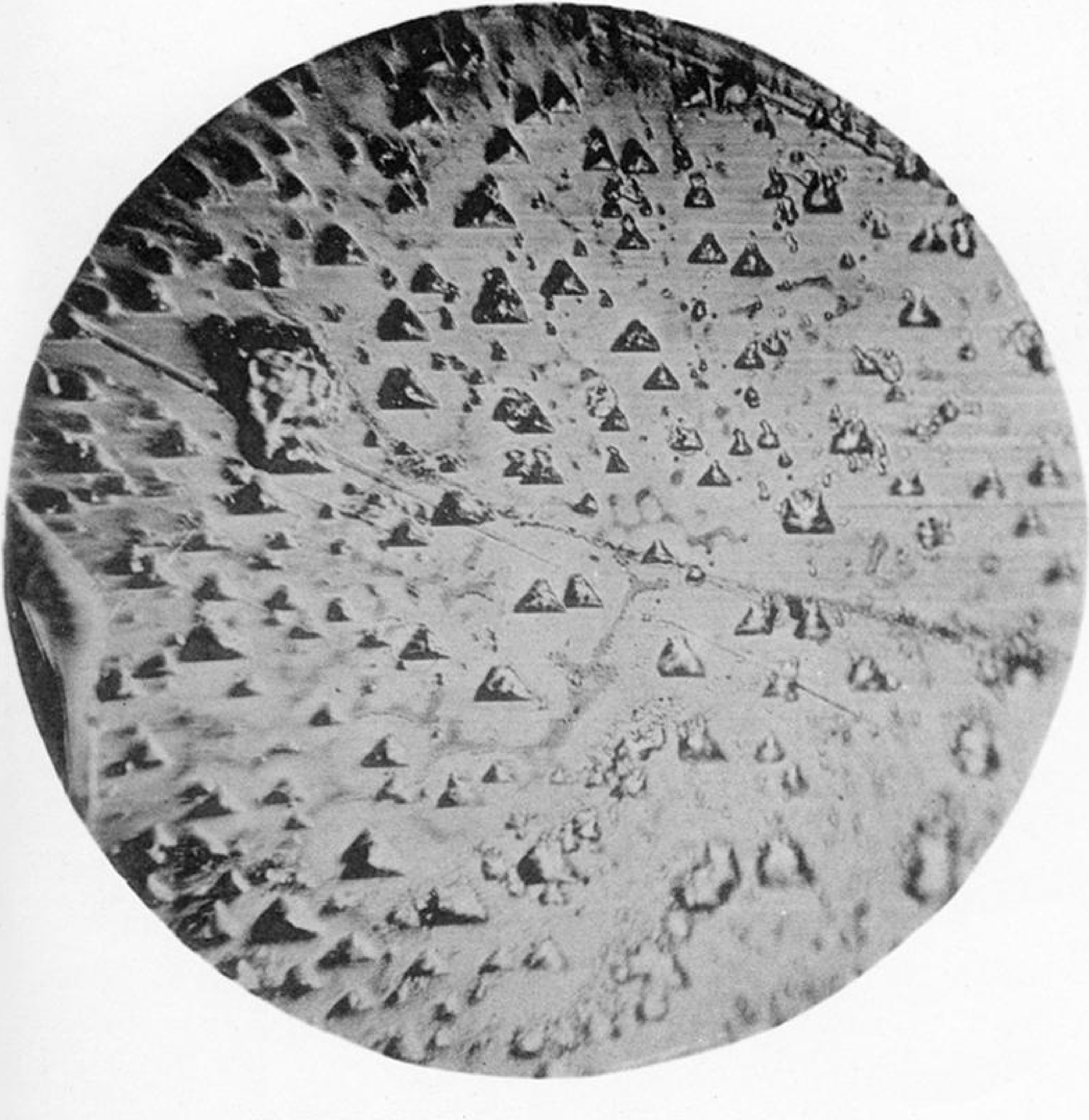


Fig. 26. CADMIUM × 1000.

Fig. 27. Cadmium × 1000.

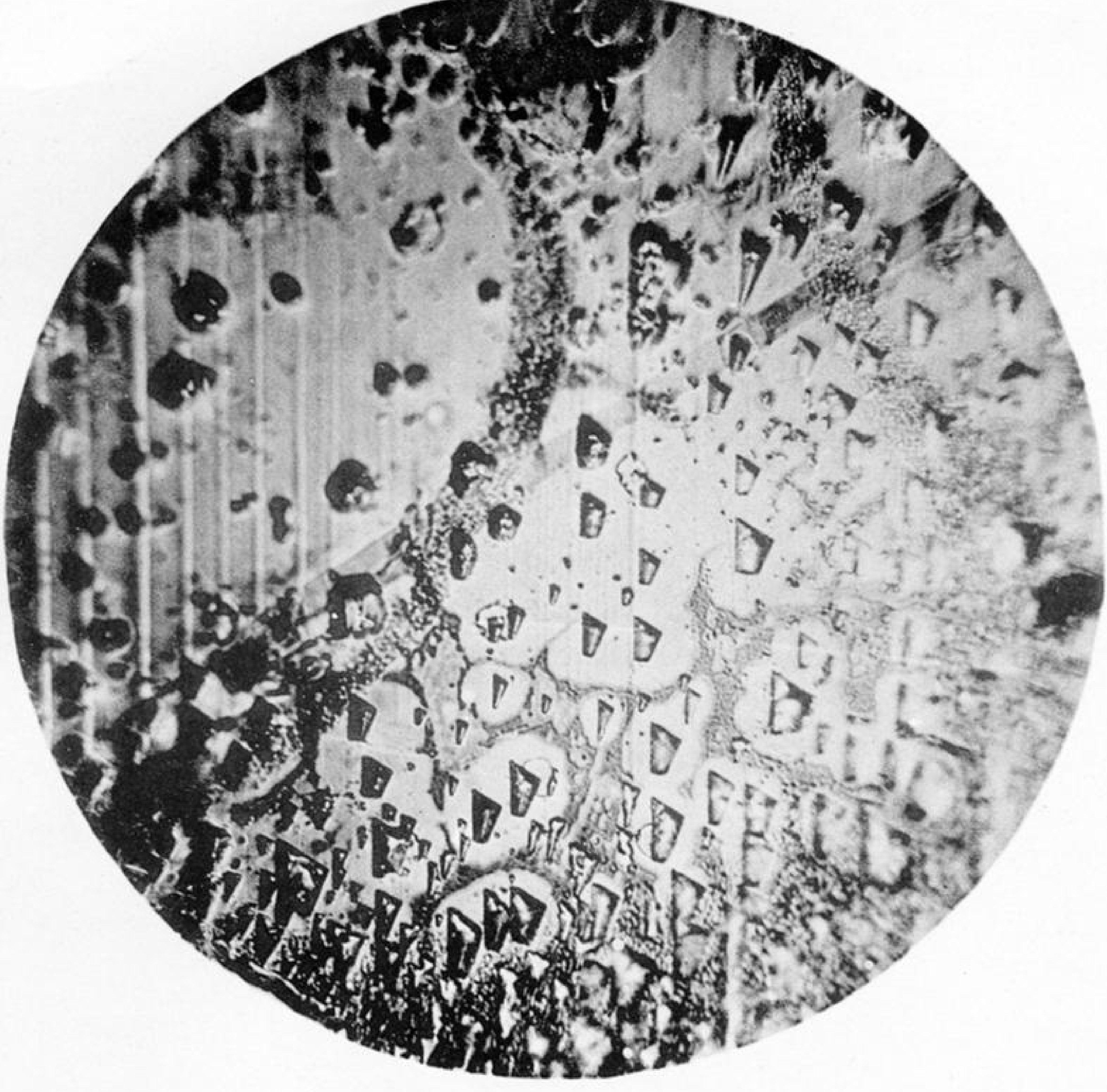


Fig. 28. Cadmium × 1000.

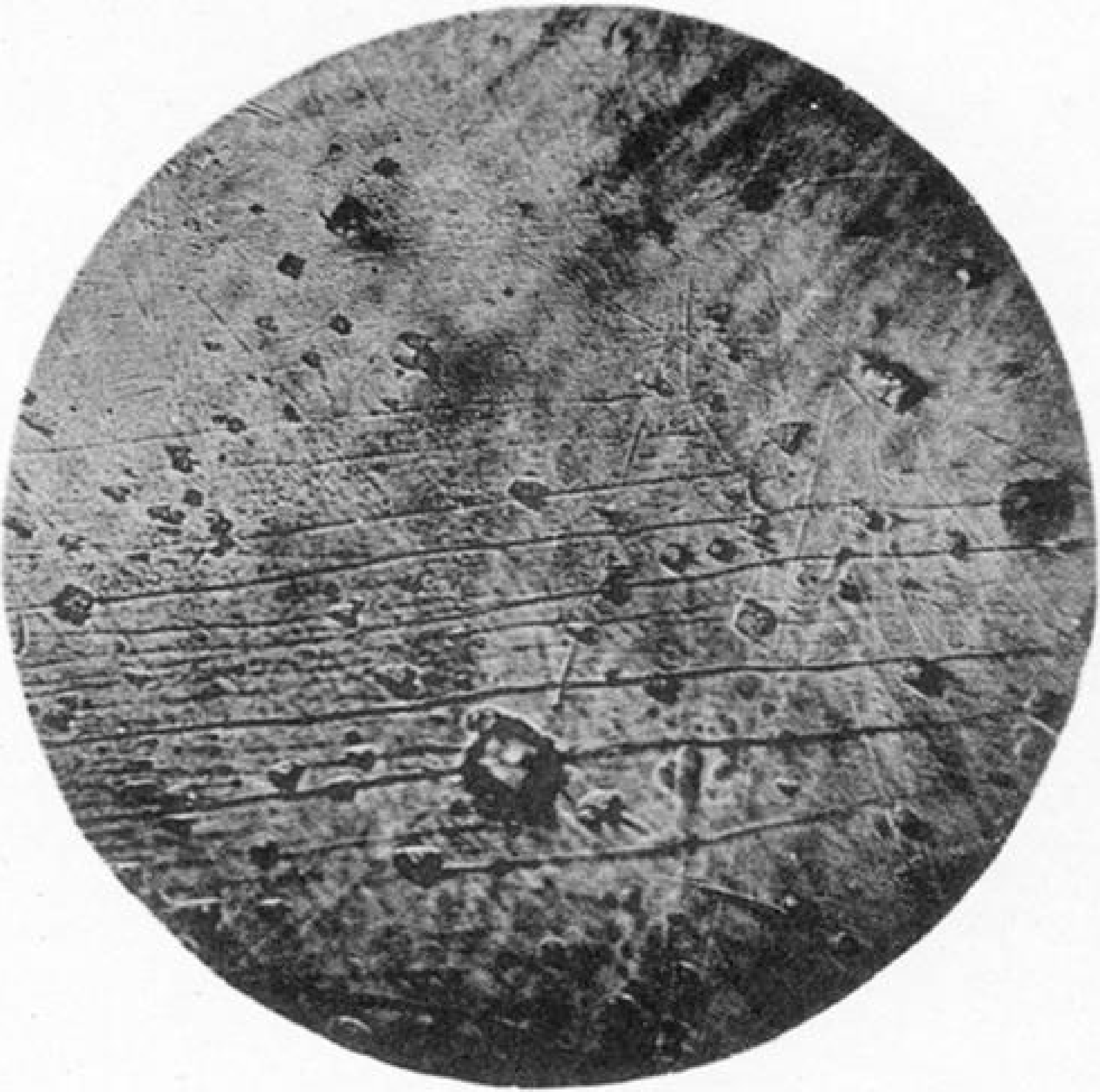


Fig. 29. Iron × 750.

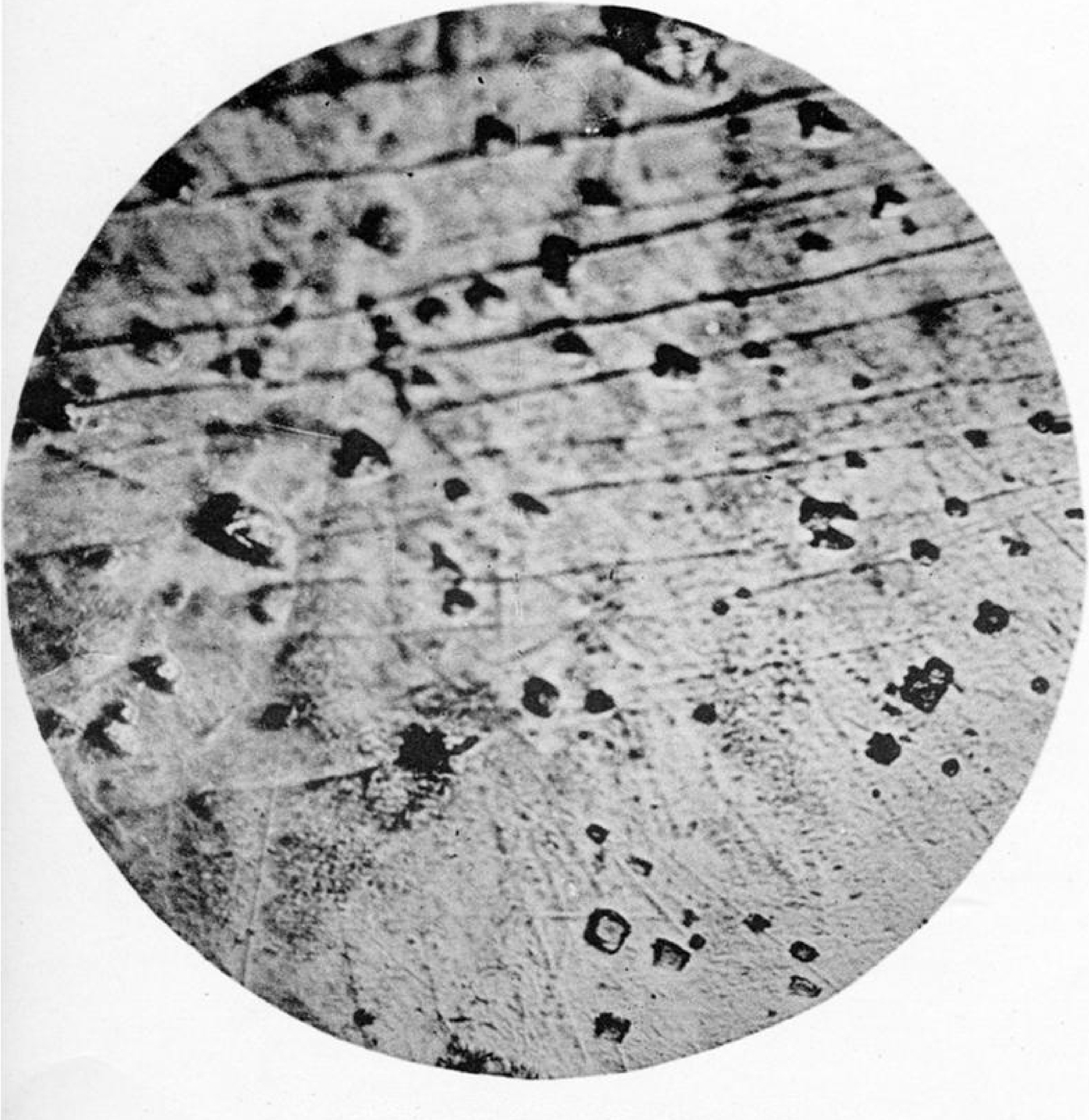


Fig. 30. Iron × 1000.

Fig. 31. Iron × 45.

Fig. 32. Iron × 200.

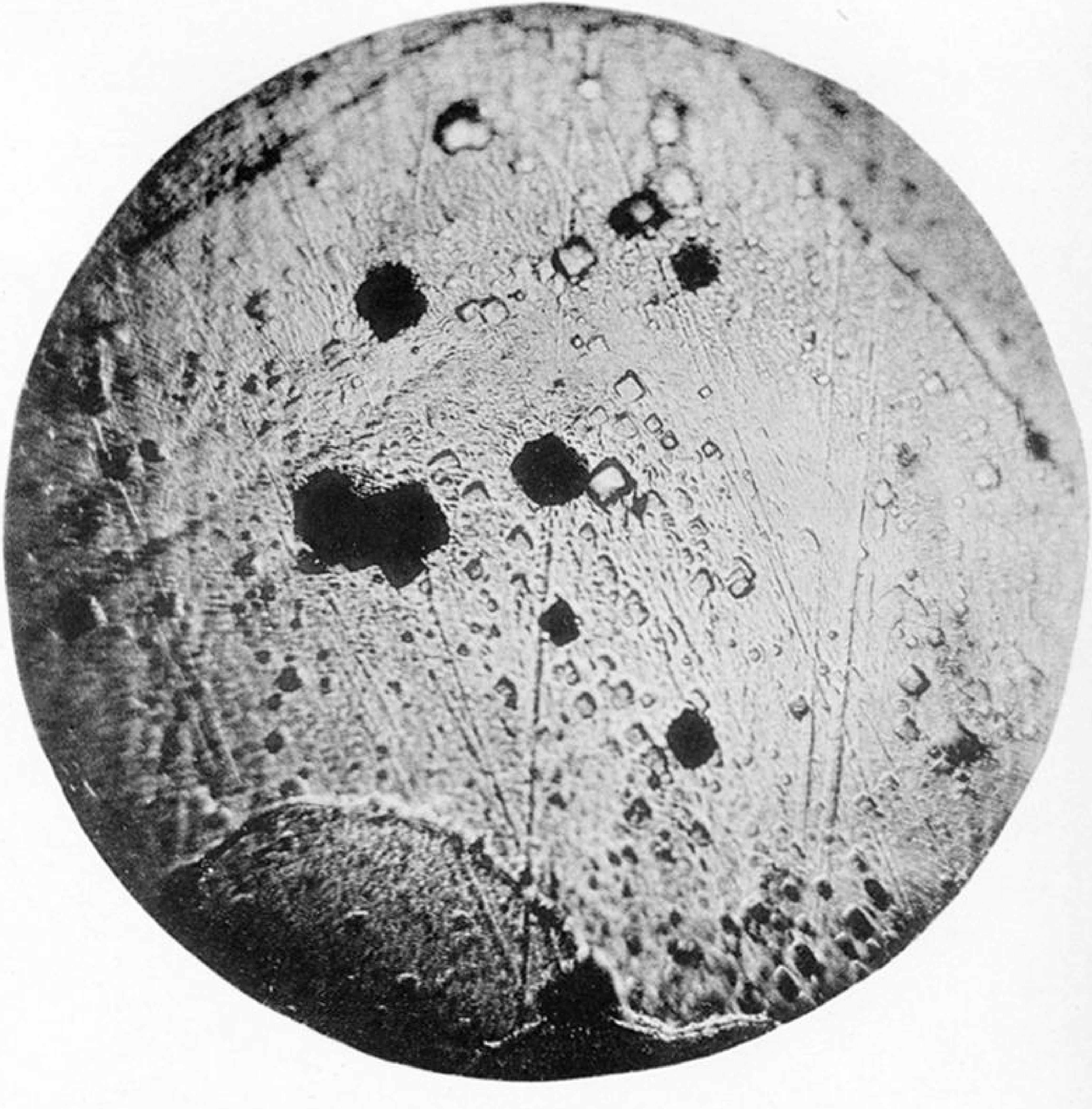


Fig. 33. Iron × 800.

Fig. 34. Copper × 1000.

Fig. 35. COPPER × 1000.

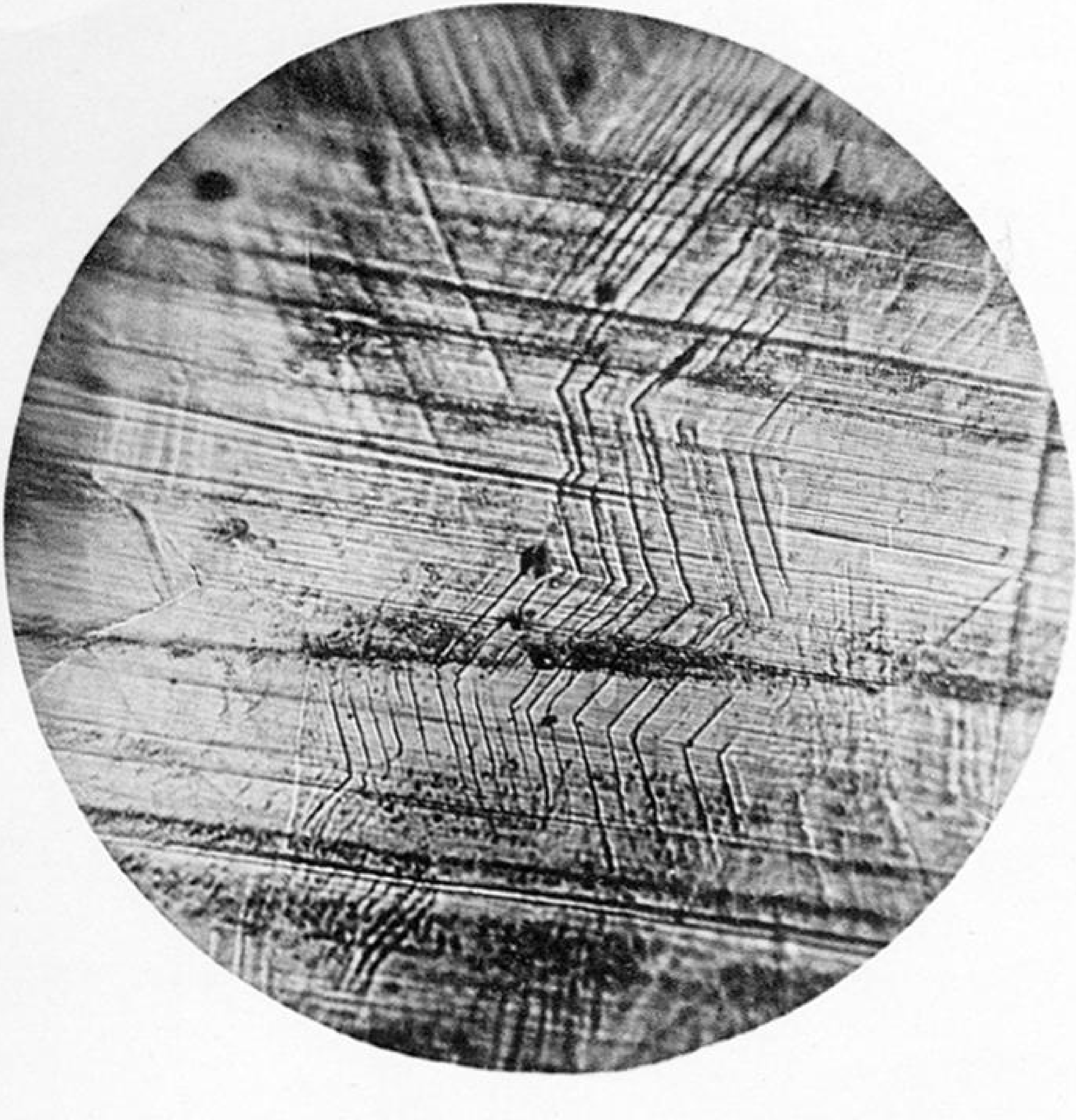


Fig. 36. Copper × 1000.

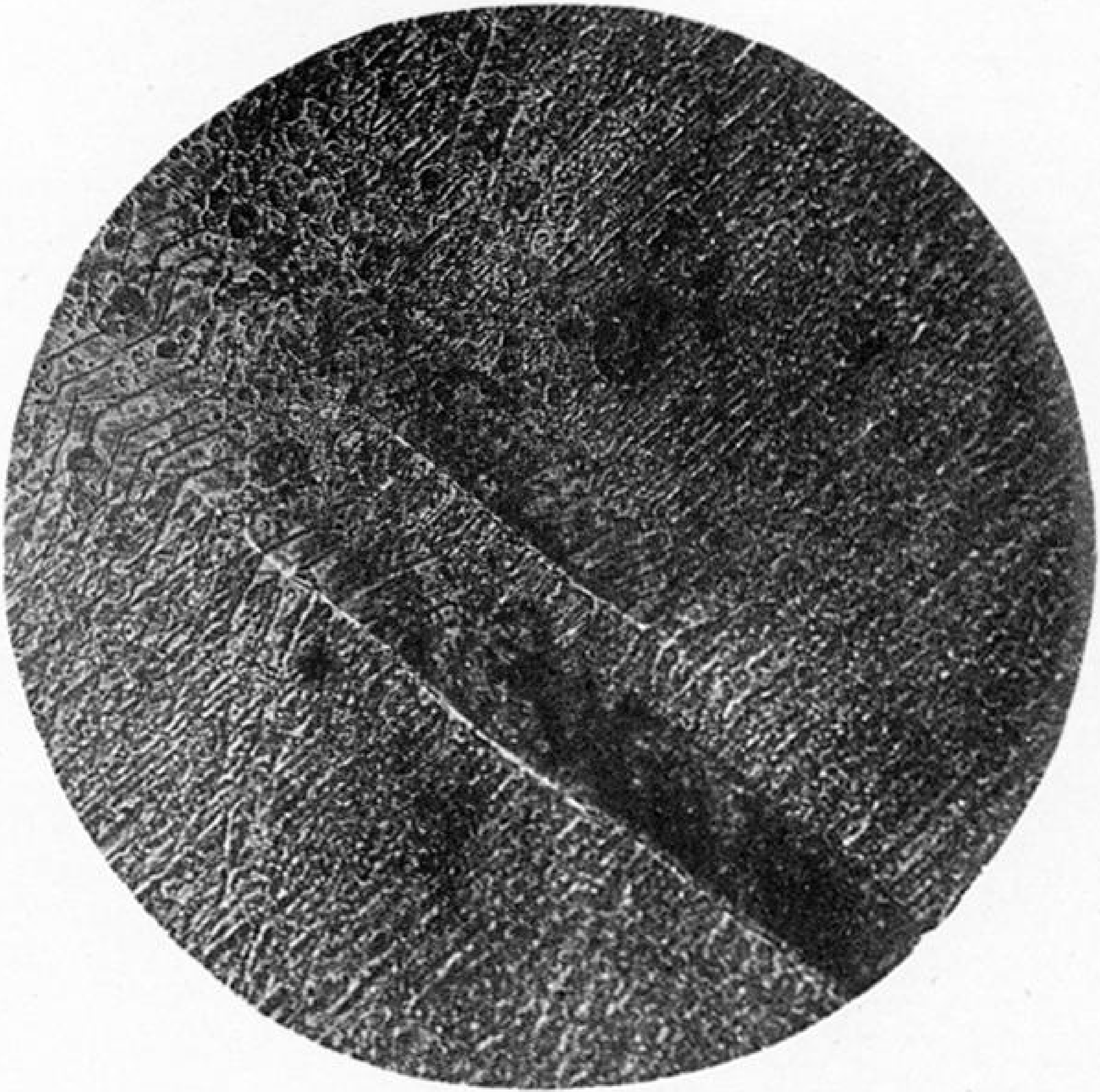


Fig. 37. Gold × 200.

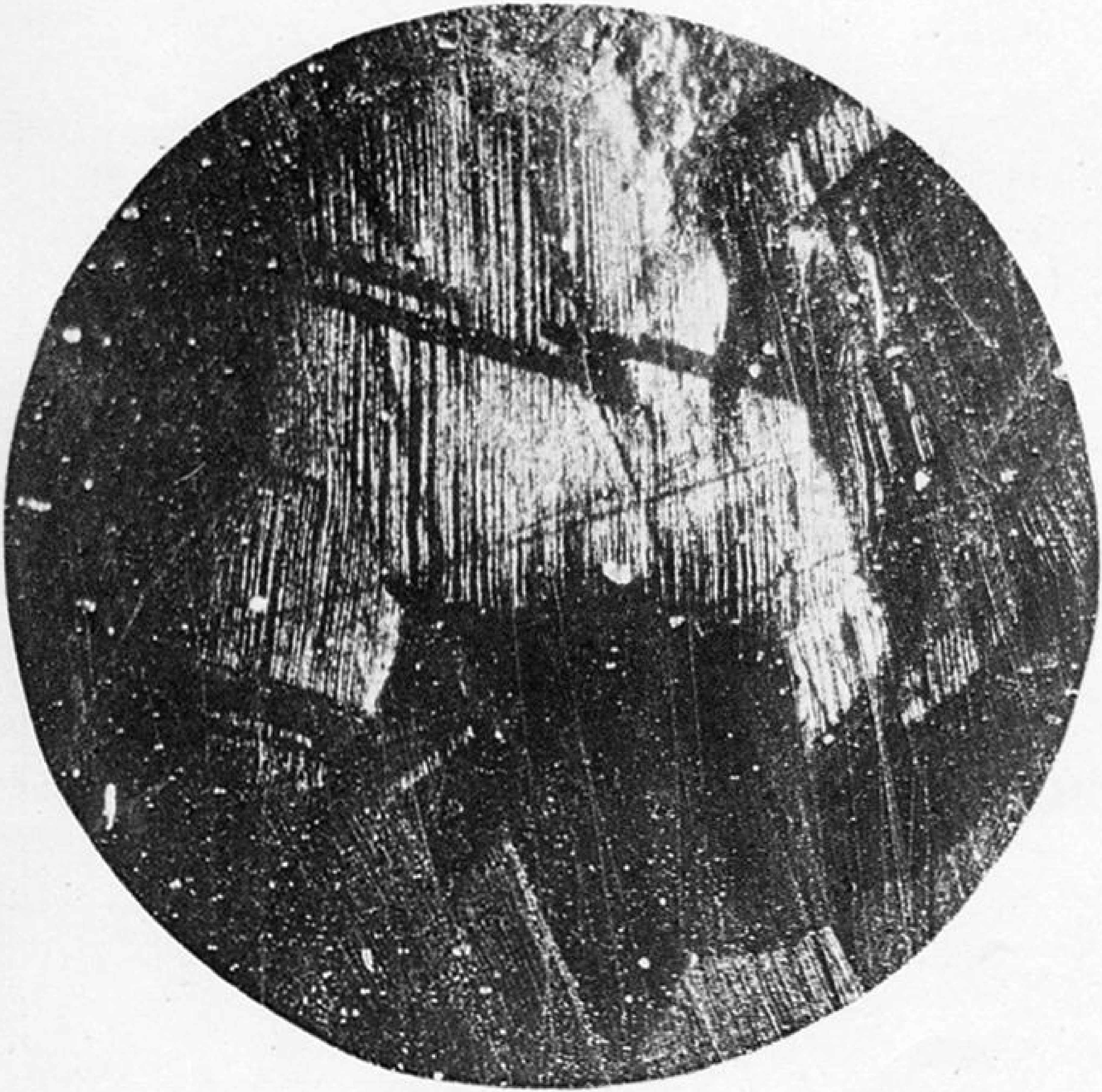


Fig. 38. GOLD × 45.

Fig. 39. Copper × 1000.

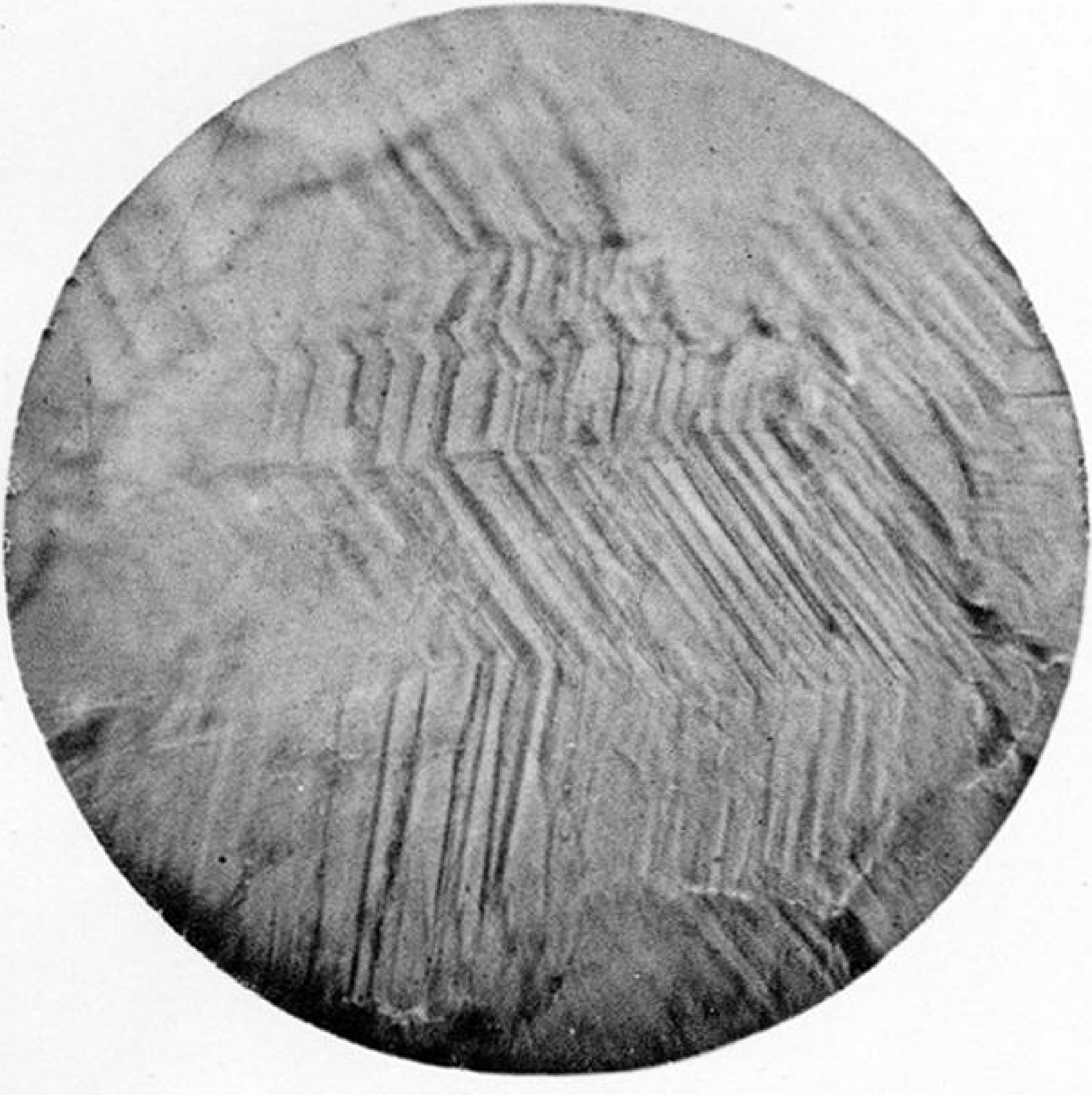


Fig. 40. Lead × 1000.

Fig. 41. Nickel × 1000.

Fig. 42. Cadmium × 100.

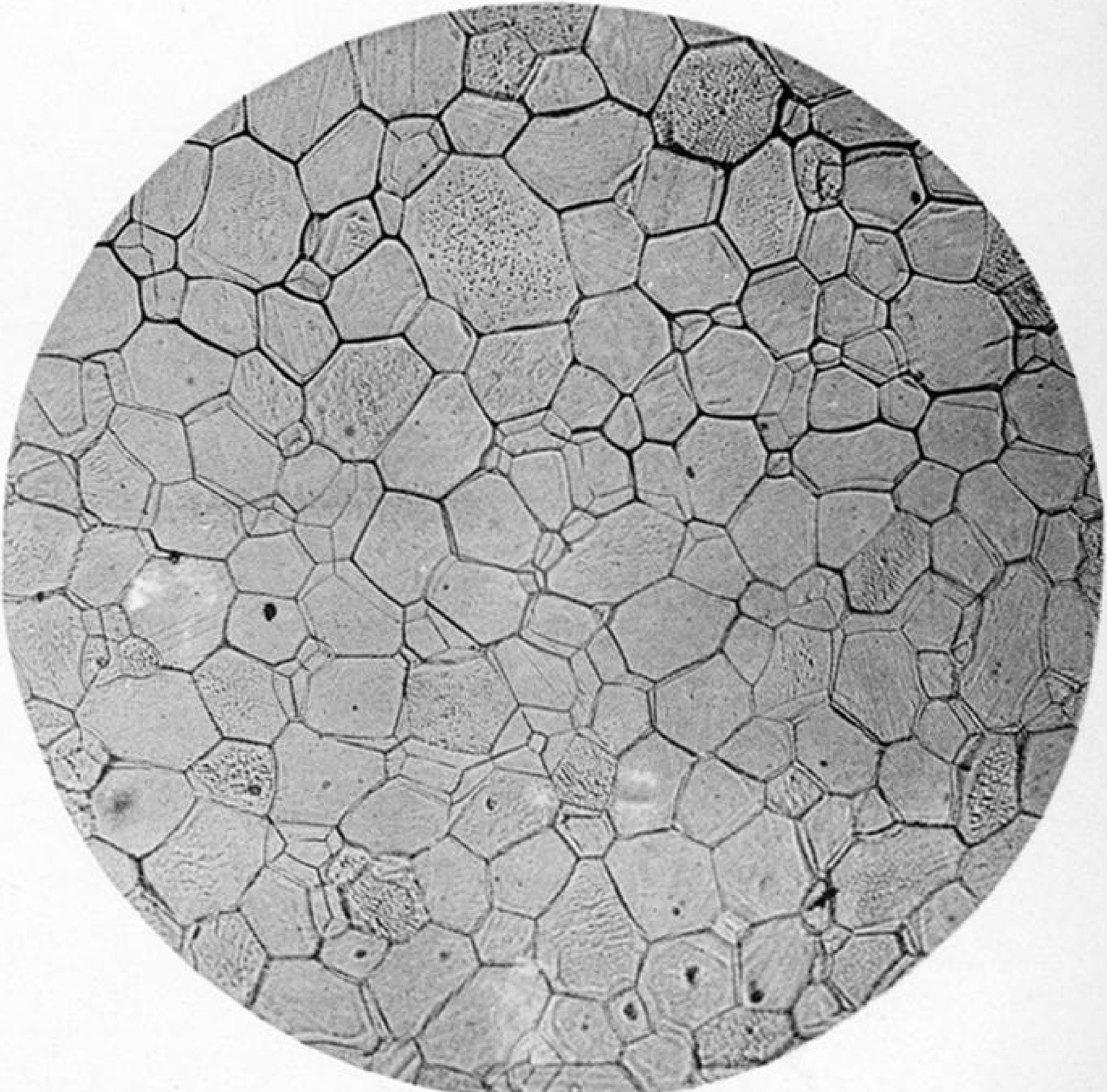


Fig. 43. Cadmium × 100.

Fig. 44. Cadmium × 1000.

Fig. 45. MILD STEEL × 1000.

Fig. 46. Lead-Tin Eutectic × 750.

Fig. 47. Lead-Tin Eutectic × 750.

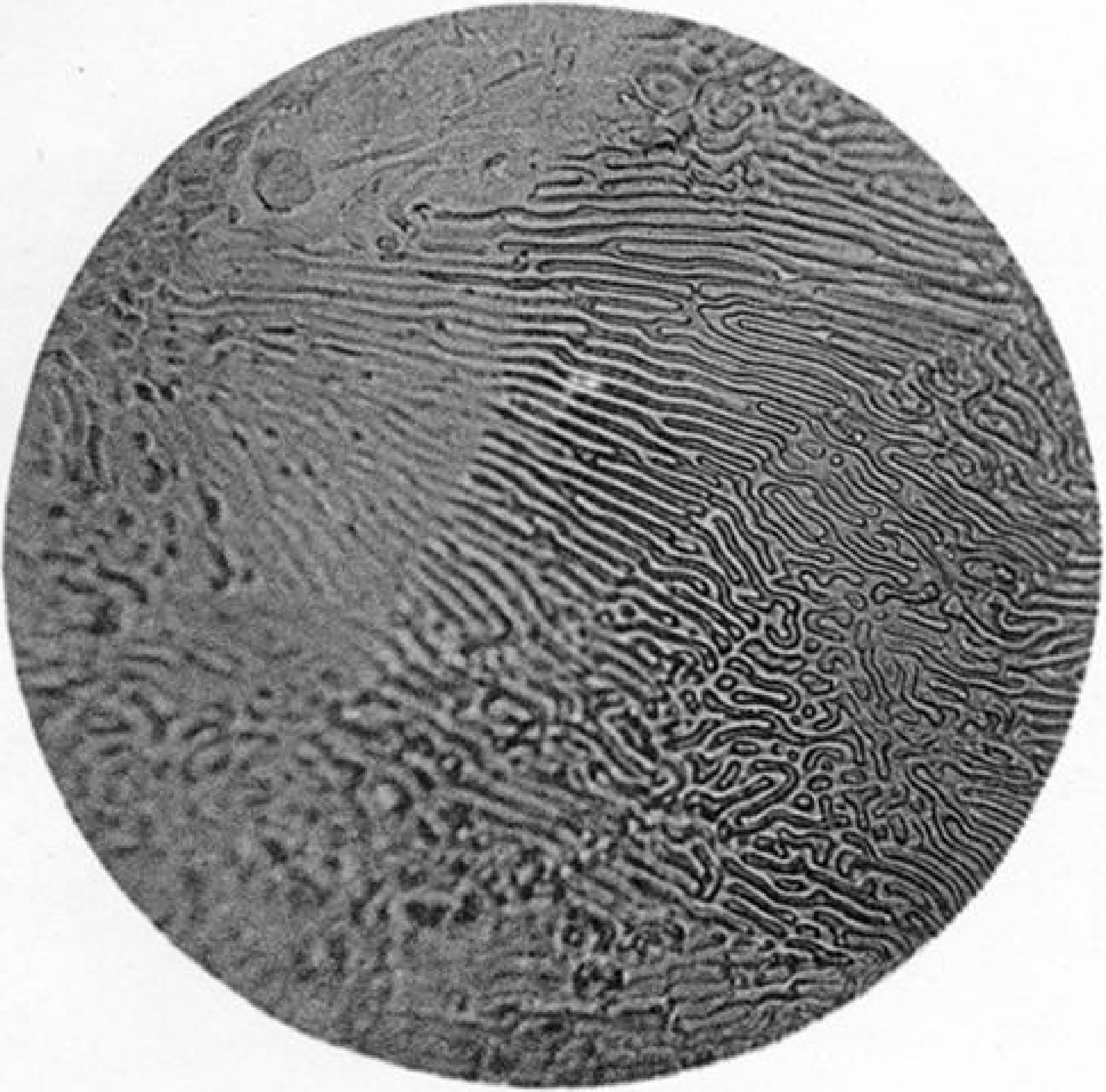


Fig. 48. Lead-Tin Eutectic × 750.

Fig. 49. Lead-Bismuth Eutectic × 1000.

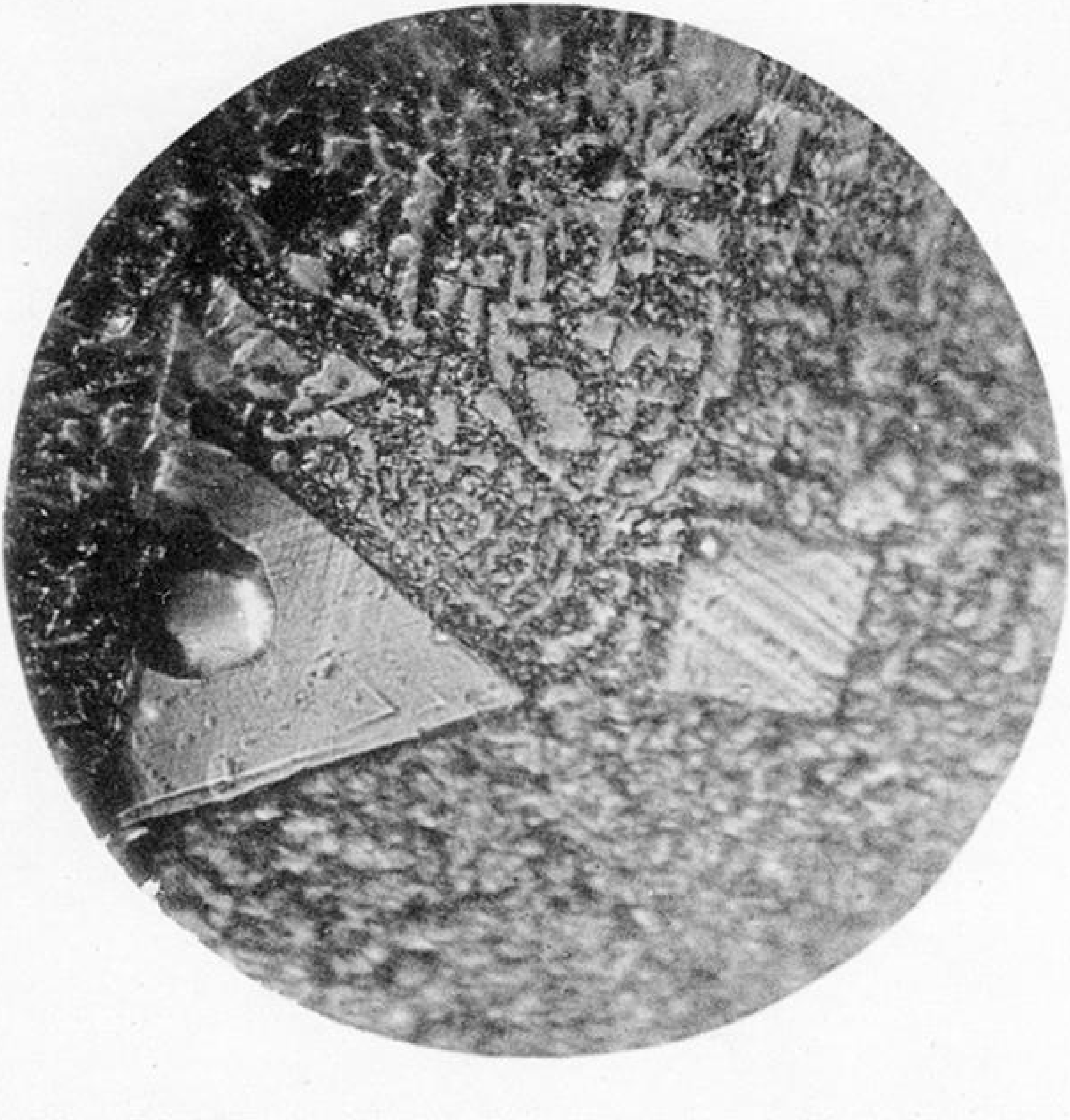


Fig. 50. Lead-Bismuth Alloy × 1000.

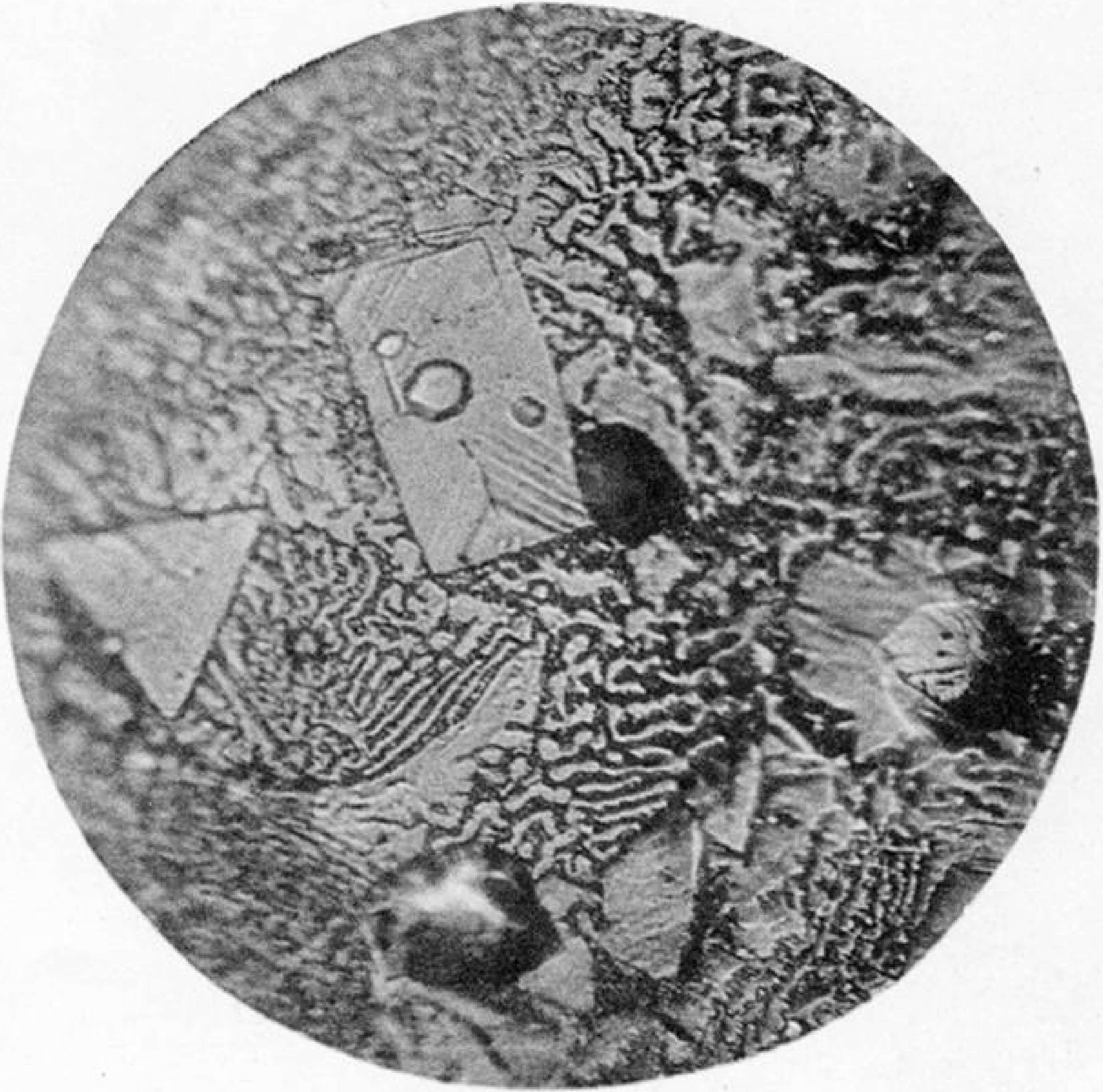


Fig. 51. Lead-Bismuth Alloy × 1000.