VI. *The Fracture of Metals under Repeated Alternations of Stress.*

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[Plates 7–9.]

It is well known that metals will break down under repeated application, and especially under repeated reversal, of stresses greatly less than those that have to be applied when the "ultimate strength" of the material is tested in the ordinary way. The researches of Wöhler have shown, for example, that iron capable of bearing about 20 tons per sq. inch of steady load will break when it is exposed to some millions of reversals of a stress of 8 or 9 tons per sq. inch, alternately in compression and extension. When the alternating stress is increased a smaller number of reversals suffices to produce rupture. On the other hand, examples such as are furnished in the balance-spring of a watch, or in a railway axle, show that very many million repetitions may be applied with impunity, provided the limit of greatest stress be kept sufficiently low. The mild steel axle of a railway carriage is exposed to many million reversals of a stress which, in some cases, approaches as high a value as 5 tons on the sq. inch, apparently with perfect impunity, for it seems probable that in the rare instances where fracture of such axles has occurred an explanation is to be found in the gradual spreading of a crack from an origin supplied by an air-bubble or other primitive defect in the material. But Wöhler's researches, which have been confirmed by other observers,* give evidence that a stress not very much greater than this, and far below not only the ultimate strength but even the "yield-point" of the metal, will produce what is called "fatigue" and bring about fracture when reversal of the stress is repeated many times.

The purpose of this paper is to describe experiments in which the microscope has been applied to study the nature of the process of fatigue by which breakdown occurs under repeated reversals of stress. The experiments have been made during the past year in the Engineering Laboratory at Cambridge. The metal chosen for experiment was Swedish iron, of high and very uniform quality. It had the further advantage for

* Particulars of the researches on this subject of Wöhler, Spangenberg, Baker, and Bauschinger will be found in Professor Unwin's 'Treatise on the Testing of Materials of Construction,' chap. xiii.

our purpose of possessing a clearly defined and fairly large crystalline structure, well adapted when polished and etched to exhibit the characteristic lines known as "slip-lines" or "slip-bands," which appear in ordinary testing when any portion of the material has passed its limit of elasticity under strain.* We used the metal in the form of rods with a rectangular section, the dimensions being approximately 0·3 inch by 0·1 inch, and to make the structure as uniform as possible these were in all cases annealed by being kept for about two hours at a dull red heat, while enclosed in a tube filled with lime, in a muffle furnace. One of the surfaces of each rod was polished

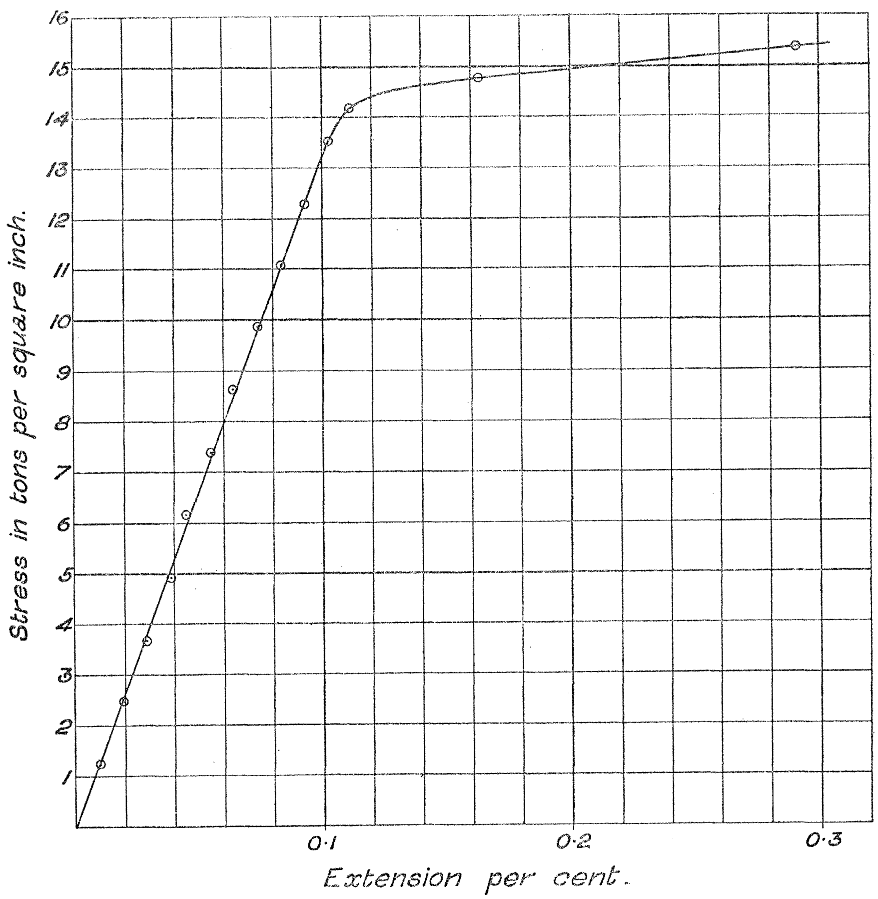

Fig. 1.

and etched, and the rod was subjected to reversals of stress by bending, so that the polished surface was alternately extended and compressed. This was done, as in Wöhler's original experiments, by making the rod project from a revolving shaft with a load on the projecting end. As the process went on the rod was from time to time examined under the microscope, and in several cases photographs of the same crystals were taken at each stage to record the progressive effect of repeated reversals of stress.

* Ewing and Rosenhain, "The Crystalline Structure of Metals" (Bakerian Lecture, 1899), 'Phil. Trans.,' A, vol. 193, p. 353.

A tensile test of the Swedish iron rod used in these experiments, carried out in a testing machine in the usual manner, showed a breaking strength of 23·6 tons per sq. inch (reckoned on the original area of section), with an ultimate extension of 0·8 inch in a length of 3 inches, and a contraction of area at the break amounting to 61 per cent. There was a well-marked yield-point when the stress reached the value of 14·1 tons per sq. inch. The diagram, fig. 1, shows the relation of extension to load up to this yield-point as measured by a microscope extensometer designed by one of the authors. It will be seen from this that the extension remains proportional (as nearly as can be judged) to the load, up to a stress of about 13 tons per sq. inch. The value of YOUNG's modulus, deduced from these measurements, is 13,200 tons per sq. inch.

The apparatus for applying repeated reversals of stress is shown in fig. 2. There *a* is the specimen under observation. It projects from the end of a shaft which was

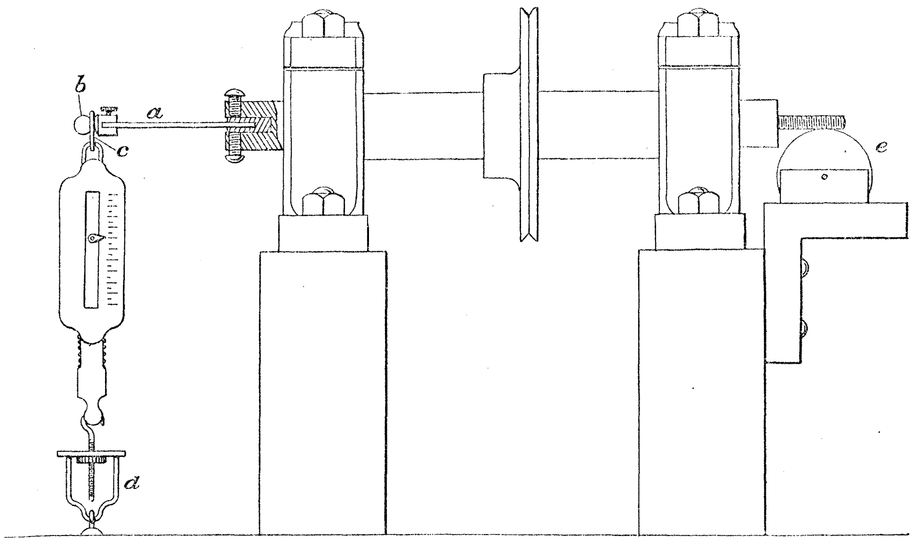

Fig. 2.

caused to rotate, by means of an electric motor, at a speed of about 400 revolutions per minute. To the outer end of the specimen a load was applied causing a bending moment. This was done by attaching a brass cap, *b*, which turned freely in a steel ring, *c*, the ring being pulled downwards with a steady force which was measured on a spring balance. The screw coupling, *d*, allowed the load to be adjusted to any desired amount. The number of reversals of stress was recorded by a revolution counter, *e*. The specimen under test was filed to a uniform rectangular section of about 0·3 inch by 0·1 inch. Part of one of the broad faces was polished and was, in general, etched by dilute nitric acid. The specimen was inserted in the grip at the end of the shaft, adjusted to run true, and the desired load was applied. After making a certain number of reversals the specimen was taken out for microscopic examination; it was then replaced for a further run, and so on, no difficulty being experienced in replacing it each time in the same position as at first.

Before the experiments were made it had been conjectured that the destructive effect of repeated alternations of stress might be ascribed to a loosening of the inter-crystalline cement rather than to damage of individual crystals. Previous experiments had shown that in fracture by ordinary progressively augmented strain the material gives way, in general, not at boundaries, but through the crystals themselves,* but it seemed possible that the effect of repeated straining might be different in this respect. By way of testing the point the experiment was made of subjecting an unetched specimen to many reversals of stress, in order to see whether the inter-crystalline boundaries became apparent as they would do if yielding took place between each crystal and its neighbours. Nothing of the kind was seen, though the boundaries in some instances could be traced through the development in different directions of slip-bands over individual neighbouring crystals. And later experiments, which will now be described, demonstrated that the mischief which is done by repeated straining occurs in quite a different way.

In experiments made with stresses ranging from 14 down to 9 tons per sq. inch it was found that fracture ultimately resulted in all cases. The course of the break-down was as follows :—The first examination, made after a few reversals of the stress, showed slips-lines on some of the crystals, on many of them if the stress was comparatively great, but on a few only if the stress did not much exceed the lower limit named above (of 9 tons per sq. inch). At this early stage the slip-lines were quite similar in appearance to those which are seen when a simple tensile stress exceeding the elastic limit is applied. Viewed under vertical illumination they appeared as fine dark lines. After more reversals of stress additional slip-lines appeared, which had not been visible in the first instance, but the most conspicuous feature was that those which were visible before became far more distinct and showed a tendency to broaden. After many reversals they changed into comparatively wide bands with rather hazily defined edges, losing entirely the fine and sharp character which slip-lines present when they first appear. As the number of reversals increased this process of broadening continued, and some parts of the surface became almost covered with dark markings made up of groups of broadened lines. When this stage was reached it was found that some of the crystals had *cracked*. The cracks occurred along broadened slip-bands; in some instances they were first seen on a single crystal, but soon they joined up from crystal to crystal, until finally a long continuous crack was developed across the surface of the specimen. When this happened a few more reversals brought about fracture.

In this description we have provisionally named a lower limit of 9 tons per sq. inch, but the experiments give grounds for believing that an even smaller stress will produce fracture in a similar manner if the process of reversing the stress is continued sufficiently long. There is clear evidence that with 9 tons per sq. inch fracture results. But we have also observed that with 8, and even 7, tons per sq. inch slip-

* EWING and ROSENHAIN, *loc. cit.*, p. 372.

lines appear, and that after many reversals they become accentuated and broaden in the manner that has been described. There is, therefore, a strong presumption that reversals of a stress of 8, or even 7, tons would ultimately develop cracks in the same manner as they are developed by stresses of 9 tons per sq. inch and over.

The destructive process, of which the above is a brief account, is illustrated in the accompanying micro-photographs (Plates 7–9).

The first series show part of a specimen which had been subjected to a stress the maximum value of which, close to the grips, was 14·3 tons per sq. inch. In this series the magnification is 150 diameters. Fig. 3 was taken after 5000 reversals had been given. A few of the crystals exhibit signs of slip, the slip-lines being still fairly fine and sharp. Two crystals in the photograph are seen to have yielded more than the others. Figs. 4 and 5 show the same set of crystals after 40,000 and 60,000 reversals of stress respectively. In fig. 4 a good many more crystals show signs of slip, and the slip-lines which appeared in fig. 3 are far more strongly defined. In some cases it will be seen that the lines have so broadened out as to run together and form dark patches on the surface of the crystals. In fig. 5 a still further breaking up of the surface by slip has occurred. At this stage, and probably earlier, some of the slip-bands have developed into small cracks. Such a crack is seen near the top right-hand corner of the figure, first of all close to a crystalline boundary, and then in steps across the next crystal. On the latter crystal two systems of slip-bands had formed at right angles to one another and at about 45° to the direction of stress. Only one system is clearly visible in the photograph, but it will be seen that the crack runs in steps along both. Fig. 5 shows not only the development of this crack, but also a general increase in width, length, and number of the slip-bands. This was practically the final stage, so far as this portion of the surface was concerned, for the specimen broke after another 10,000 reversals along a crack outside the field of these photographs.

When viewed in this state it is not practicable to tell how many of the slip-bands have actually developed into cracks, but this is readily seen when the specimen is re-polished and re-etched. This treatment obliterates any ordinary slip-bands which are steps marking differences of surface level, but any cracks remain visible. The specimen which gave this series of photographs was accordingly re-polished sufficiently to clear away the slip-bands, and was re-etched. This left the cracks alone visible, rather accentuated indeed, for the sides of the cracks are to some extent eaten away by the acid, and hence the width of the crack is increased. Fig. 6 shows the same part of the specimen as figs. 3, 4, and 5, after re-polishing and re-etching. The slip-bands have disappeared, except where they have formed cracks. A careful comparison of this with fig. 3 will show where cracks have formed. The most conspicuous crack is at AA, and its zig-zag character as it follows the two directions of slip-bands across one of the crystals is specially noticeable.

The specimen illustrated in the next photograph, fig. 7, had been subjected to

170,000 reversals of a stress of 12·3 tons per sq. inch, at which it broke. The spot shown (magnified 150 diameters) is a little way further from the grips than the crack through which the specimen actually broke, but another severe crack is seen running across the centre of the figure. Comparing this with fig. 5, it will be at once seen that there are far fewer lines due to slip upon each individual crystal than in the former specimen. Fig. 8 shows the same spot after re-polishing and etching. Comparing this with fig. 6 it is seen that a greater proportion of the slip-lines appear in this instance as cracks after re-polishing. The maximum stress is less here than in the former example, and more than twice as many reversals were required to bring about fracture. This agrees with what has been found for all other specimens broken, viz., the lower the stress the fewer the slip-lines upon each crystal, but the greater proportion of these actually develop into cracks under the more numerous reversals to which the less severely stressed specimen is exposed.

The photographs described above are on rather too small a scale for the actual changes in the slip-lines themselves to be clearly seen, and these are better illustrated by the next series, figs. 9–12. These show with a magnification of 1000 diameters a small part of the surface of another specimen of the same iron which was subjected to reversals of 12·4 tons per sq. inch. Fig. 9 is taken after 1000 reversals. The slip-bands which have formed are very faintly visible as fine lines upon the surface of the crystal. Fig. 10 is after 2000 reversals; the slip-bands seen in fig. 9 are now more distinct, and some new ones on the right of the crystal are fairly strongly defined. Fig. 11 is after 10,000 reversals; some of the slip-bands now show a decided tendency to broaden out and those upon the right have extended further across the crystal. Fig. 12, taken after 40,000 reversals of stress, shows further broadening out and spreading of the slip-bands. At this stage it could be seen by the focussing that this broadening was due to a heaving-up of the surface of the crystal in the neighbourhood of each slip-band, the markings being decidedly above the level of the other parts of the crystal. It is to be conjectured that the action is of the kind indicated in the sketch (fig. 13) where (a) represents an ordinary slip-band seen in section at right angles to its length, and (b) represents the effect of reversals of stress upon it. Very little further change took place in the particular crystal of figs. 9–12 as further reversals were applied, the specimen breaking elsewhere after 160,000 reversals. It has been noticed in this respect that when once an incipient crack begins to form across a certain set of crystals, the effect of further reversals

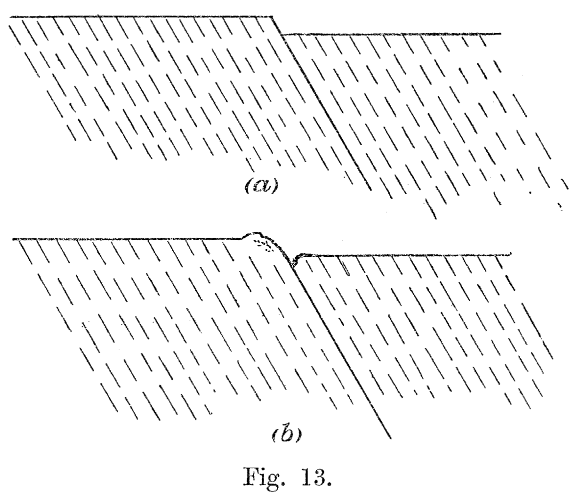

Fig. 13.

is mainly confined to the neighbourhood of the crack, other crystals (as was the case with that illustrated in figs. 9–12) changing but slightly.

Fig. 14 (Plate 8) shows a different part of the same specimen (after it had broken), also under a magnification of 1000 diameters. The broad band in the middle of the crystal is a crack which has developed along what was originally a line of slip. The heaving-up of the surface along the edges of the crack is well marked and may be compared with similar appearances at the edges of slip-bands in other parts of the photograph.

The stresses which are stated here are in all cases calculated from the observed load, as measured by the spring balance, acting at the end of projecting beam or "cantilever," and they are the values which (on the ordinary theory of bending) are reached at a place close to the clamp. It was observed, however, that the destructive effects of reversals were not confined to the metal immediately adjacent to the clamps, but extended in most cases for a considerable way towards the loaded end of the specimen. The development of slip-bands, and their gradually widening and final conversion into cracks, occurred in some cases at least half-an-inch from the clamp, at a place where the fixing of the specimen could not disturb the distribution of stress in any way.

In another experiment the load was such as to produce a maximum stress, close to the clamp, of 9·2 tons per sq. inch, and 800,000 reversals were given. It was then seen that the greater number (though not all) of those crystals which closely adjoined the place where the specimen was clamped showed signs of repeated slip. Further away from the clamp the slip-lines became less numerous; but they were plainly seen on individual crystals as much as half-an-inch from the clamp. At the most distant places where slip-lines were plainly apparent the stress was only 7·3 tons per sq. inch. It was clear that a stress no greater than this was sufficient to develop slips, under many reversals, and that the lines so produced became accentuated as the process went on.

This was confirmed by another experiment in which the maximum stress, close to the clamp, was only 6·9 tons per sq. inch. After 3,000,000 reversals of this stress *one* slip-band was observed on a crystal a little way from the clamp. This is shown in fig. 15, where the slip-band is seen in the broadened condition which resulted from 3,000,000 reversals of stress. Prior to this, the same specimen had suffered 1,000,000 reversals of a stress of 5·3 tons per sq. inch, without showing the smallest sign of damage. It was only after increasing the stress to 6·9 tons per sq. inch that any action became apparent. It is an open question whether an isolated slip-band such as this would have led to fracture, if the process of reversal had been continued. At the conclusion of the experiment it was still confined to one crystal and it did not even extend all the way across that.

We have noticed that when lines indicating slip appear during reversals of a comparatively small stress, they are generally to be found in the central parts of individual crystals, not extending to the boundaries of the crystal.

It appears, then, that this material suffers no damage from repeated reversals of a stress of 5 tons per sq. inch; but that when the stress is raised to 7 tons per sq. inch signs of fatigue are apparent after many reversals. And further, that with a stress of no more than 9 tons per sq. inch, the damage caused by reversals is so considerable that cracks are formed and the piece breaks. In all probability fracture through the formation of cracks would occur with 7 tons also, though all that is actually demonstrated for this stress is that it causes slip-bands to appear and to become accentuated in the manner which, with greater stresses, leads to the development of cracks.

It is remarkable that these actions are brought about by stresses much below what is ordinarily understood by the elastic limit of the material. A tensile test shows proportionality of strain to stress up to 12 or 13 tons per sq. inch, with no apparent defect of elasticity. The conditions under which these experiments were made seem to exclude the possibility that vibration gave rise to local augmentation of the stresses. The manner in which the slip-lines appear shows that some crystals reach a limit of elasticity sooner than others. This is no doubt to be ascribed in part to their being so oriented that the gliding planes, on which slip occurs, are inclined in the direction which is most favourable to the action of tangential stress. But besides this, it may be conjectured that in a complex structure built up of many crystals irregular in form the distribution of stress from crystal to crystal is by no means homogeneous.

Whatever the selective action of the stress is due to, the experiments demonstrate that in repeated reversals of stress certain crystals are attacked and yield by slipping, as in other cases of non-elastic strain. Then, as the reversals proceed, the surfaces on which slipping has occurred continue to be surfaces of weakness. The parts of the crystal lying on the two sides of each such surface continue to slide back and forth over one another. The effect of this repeated sliding or grinding is seen at the polished surface of the specimen by the production of a *burr*, or rough and jagged irregular edge, broadening the slip-band, and suggesting the accumulation of *débris*. Within the crystal this repeated grinding tends to destroy the cohesion of the metal across the surface of slip, and in certain cases this develops into a crack. Once the crack is formed it quickly grows in a well-known manner, by tearing at its edge, in consequence of the concentration of stress which results from lack of continuity. Engineers are familiar with the development of cracks, even in the most ductile materials, when these are initiated at air-bubbles or other flaws. The present experiments show how a crack may be formed, without any flaw to serve as nucleus, the first breach of continuity being set up through repeated grinding on a plane of slip in perfectly sound metal.

The experiments throw light on the known fact that fracture by repeated reversals or alternations of stress resembles fracture resulting from a "creeping" flaw in its abruptness and in the absence of local drawing-out or other deformation of shape.

They also help to explain why it is that a piece that has been subjected to many reversals shows no apparent loss of strength or plasticity when subjected to an ordinary tensile test. So long as the reversals have not yet reached the stage of producing cracks, it is not to be expected that such a test will detect the deterioration which has occurred. The material will still yield by slipping much as at first, and neither its plasticity nor its strength need show much change.

Interesting points suggest themselves which require further investigation. It is well known that when a plastic metal such as iron is strained sufficiently to take permanent "set," it suffers a temporary loss of elasticity, which is recoverable by lapse of time, the recovery of which, as MUIR has shown, may be enormously accelerated by warming the piece to such a temperature as 100° C.* This may be ascribed to a gradual healing action which restores the resistance to sliding on the planes of slip after they have been weakened by the first severe strain. The first strain makes subsequent slipping easier, for a time, but when the material has a long enough rest recovery ensues. Probably enough a similar recovery would occur if during the application of reversals of stress long intervals of rest were allowed, and still more if during these intervals the temperature of the piece were raised. It may be conjectured that such treatment would arrest the destructive process of fatigue in its earlier stages, and give the material a new lease of life. The damage which alternating stresses produce probably depends not only on the amount of the stress and the number of alternations it suffers, but on the rapidity with which the alternations follow one another,† and on the continuity or otherwise of the alternating action.

DESCRIPTION OF PLATES.

PLATE 7.

Figs. 3–6. Fatigue of Swedish iron by reversals of a stress of 14·3 tons per sq. inch. Magnification 150 diameters.

Fig. 3 after 5,000 reversals.
Fig. 4 after 40,000 reversals.
Fig. 5 after 60,000 reversals.
Fig. 6 after 70,000 reversals, followed by re-polishing and re-etching.

* MUIR, "On the Recovery of Iron from Overstrain," 'Phil. Trans.,' A, vol. 193, p. 1.

† On this point, the experiments of OSBORNE REYNOLDS and J. H. SMITH ('Proc. Roy. Soc.,' vol. 70, 1902, p. 44) have already shown that rapid reversals are more destructive than less rapid reversals, in the sense that to make fractures result from an equal number of both, the maximum stress must be higher when the number of reversals per minute is less.

PLATES 8 AND 9.

Figs. 7–8. Fatigue of Swedish iron by reversals of a stress of 12·3 tons per sq. inch. Magnification 150 diameters.

Fig. 7 after 170,000 reversals.
Fig. 8 same after re-polishing and re-etching.

Figs. 9–12. Fatigue of Swedish iron by reversals of a stress of 12·4 tons per sq. inch. Magnification 1000 diameters.

Fig. 9 after 1,000 reversals.
Fig. 10 after 2,000 reversals.
Fig. 11 after 10,000 reversals.
Fig. 12 after 40,000 reversals.

Fig. 14. Another part of the same specimen after 160,000 reversals.

Fig. 15. Development of a slip-band by 3,000,000 reversals of a stress of 6·9 tons per sq. inch.

Fig. 3. Specimen of Swedish iron after 5000 reversals of a stress of 14·3 tons per sq. inch. × 150.

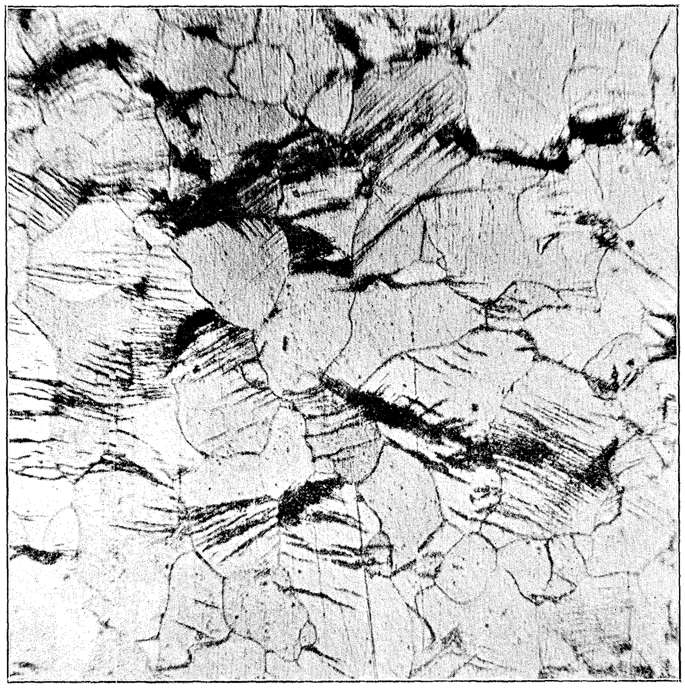

Fig. 4. Same after 40,000 reversals. × 150.

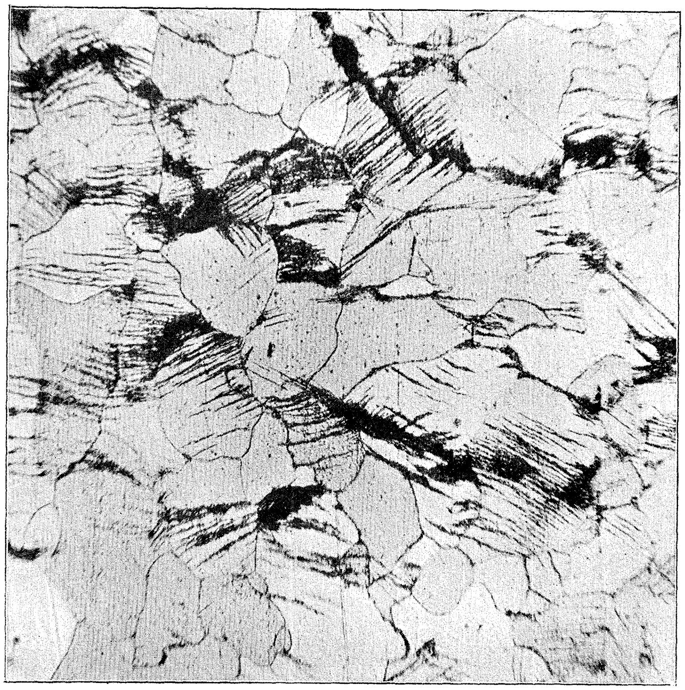

Fig. 5. Same after 60,000 reversals. × 150.

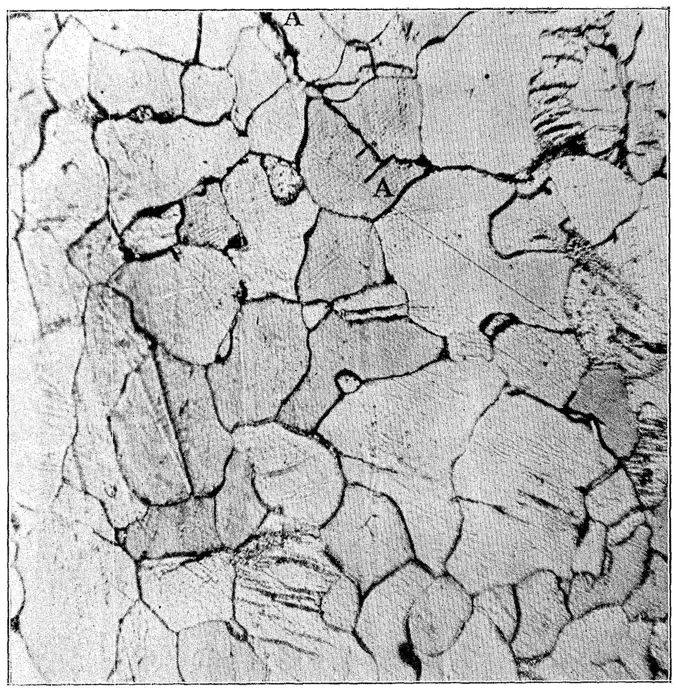

Fig. 6. Same after 70,000 reversals and re-polishing and re-etching. × 150.

Fig. 7. Specimen after 170,000 reversals of a stress of 12·3 tons per sq. inch. × 150.

Fig. 8. Same after re-polishing and re-etching. × 150.

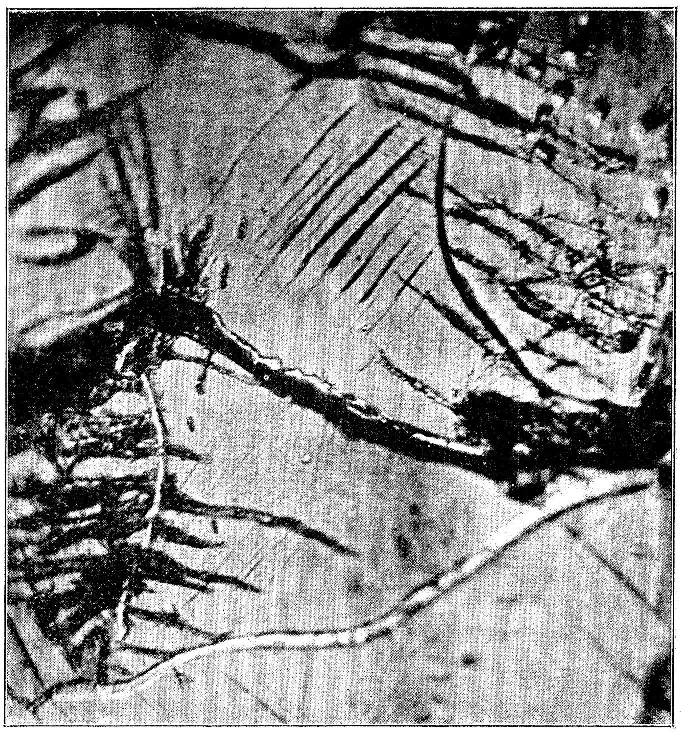

Fig. 14. Another part of the specimen of figs. 9–12, after 160,000 reversals. × 1000.

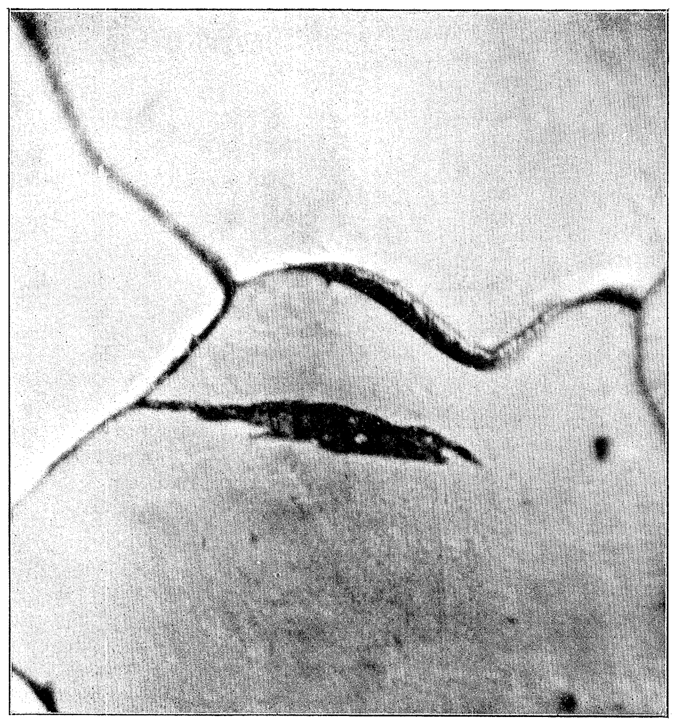

Fig. 15. Specimen after 3,000,000 reversals of a stress of 6·9 tons per sq. inch. × 1000.

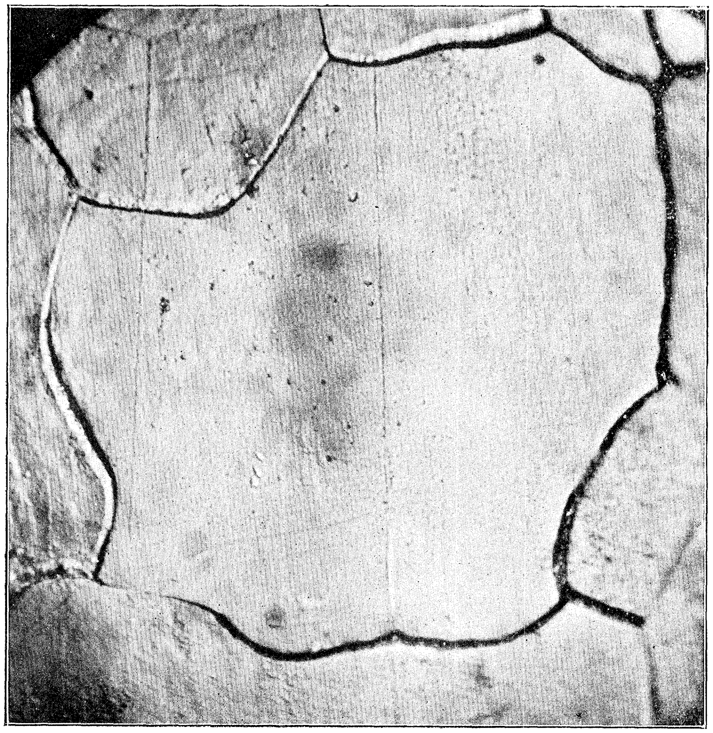

Fig. 9. Specimen after 1000 reversals of a stress of 12·4 tons per sq. inch. × 1000.

Fig. 10. Same after 2000 reversals. × 1000.

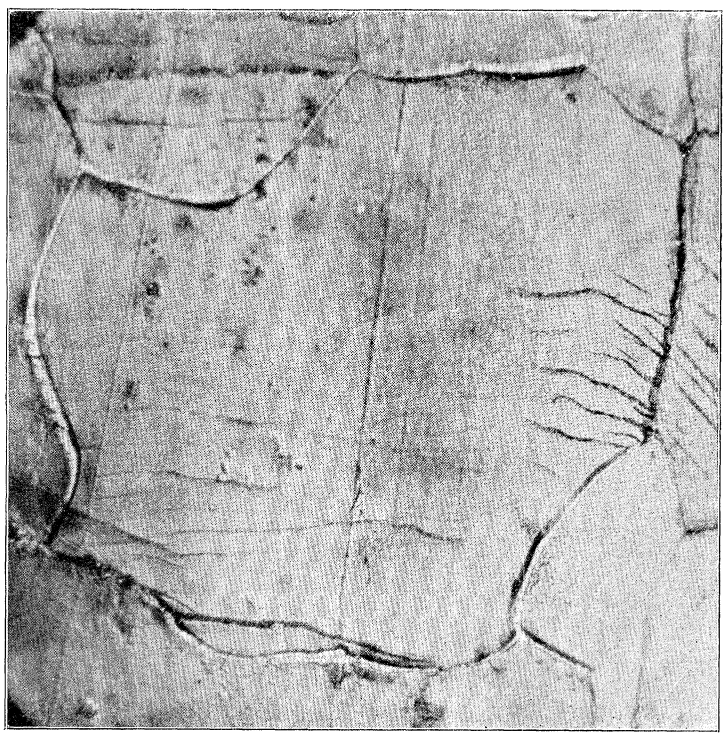

Fig. 11. Same after 10,000 reversals. × 1000.

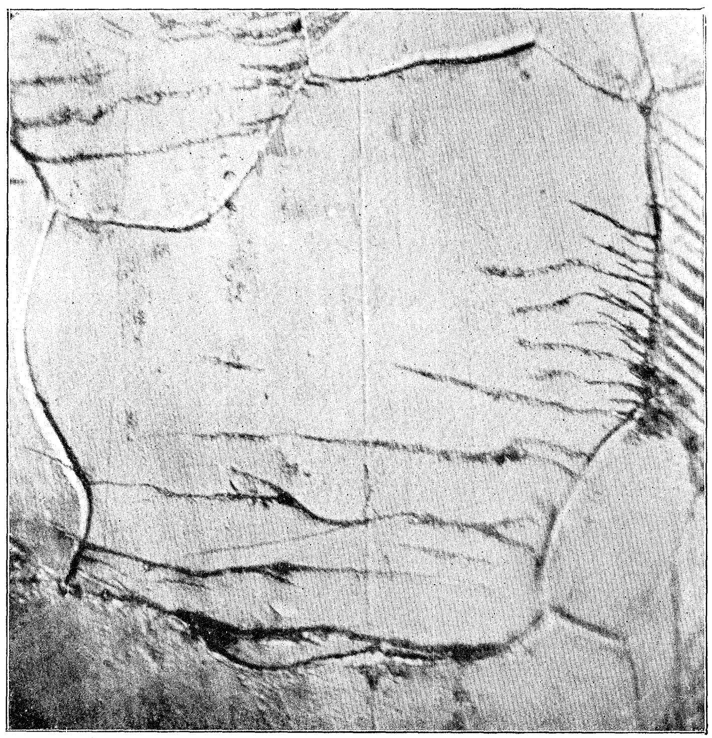

Fig. 12. Same after 40,000 reversals. × 1000.

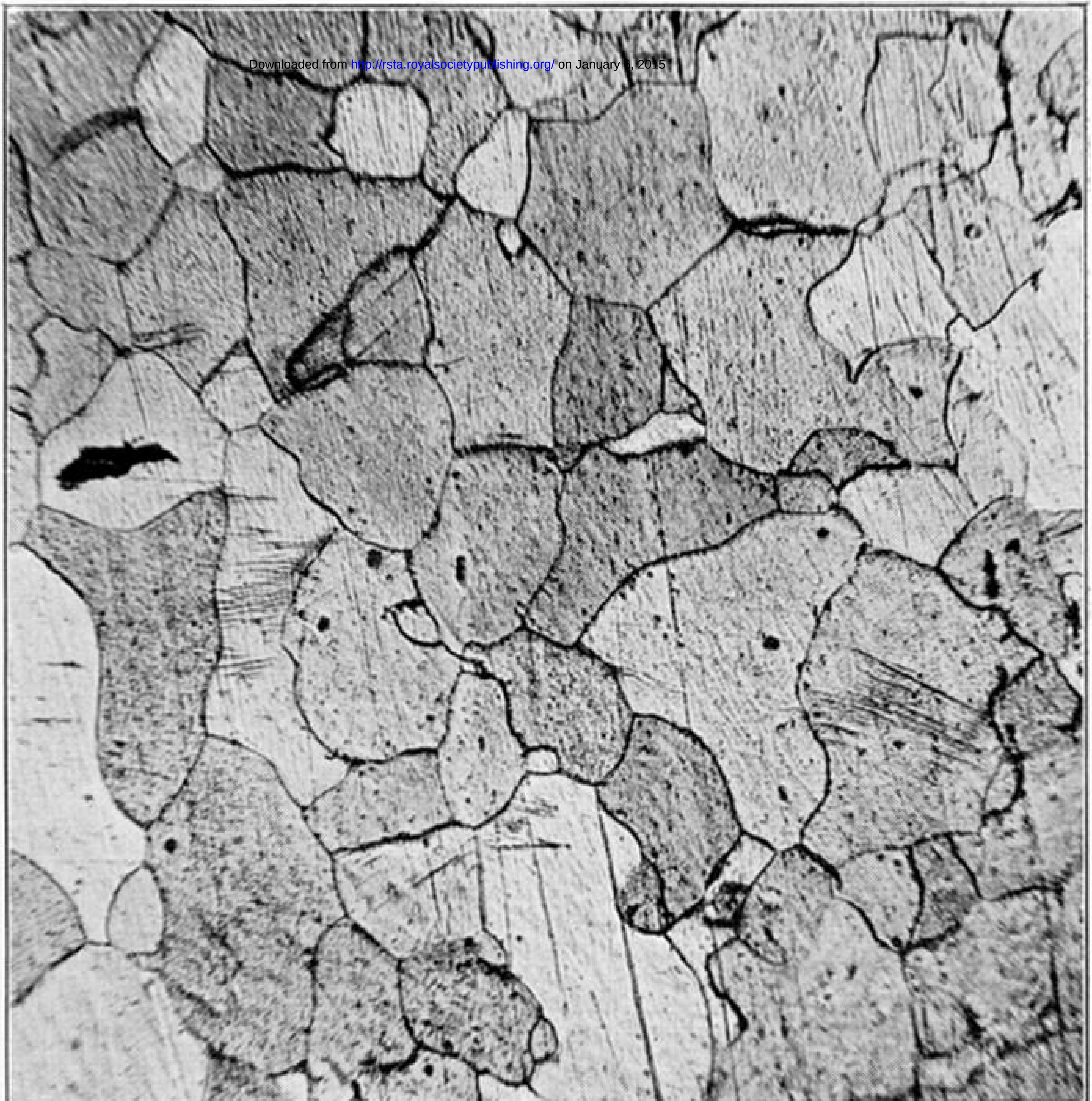

Fig. 3. Specimen of Swedish iron after 5000 reversals of a stress of 14·3 tons per sq. inch. × 150.

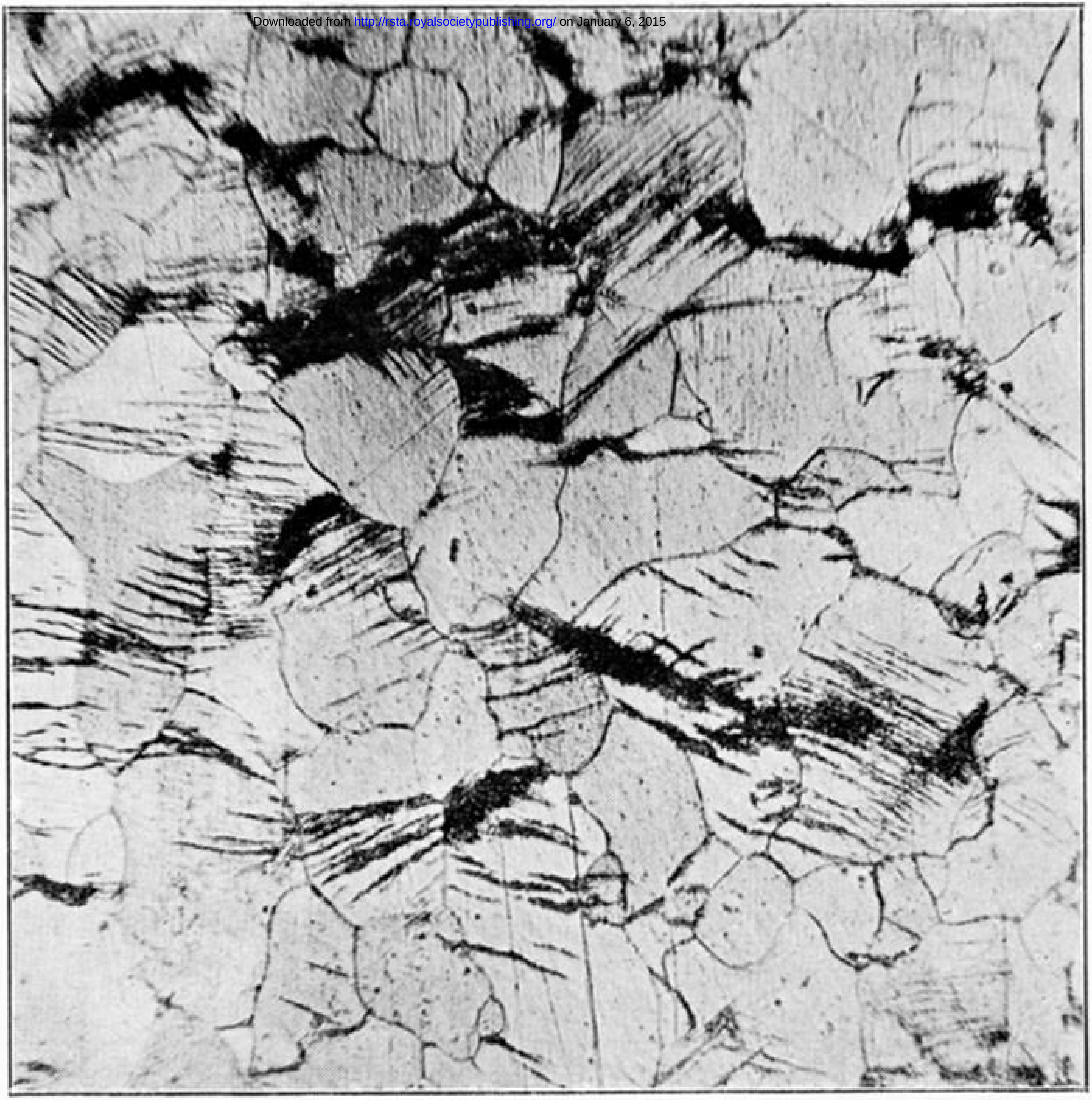

Fig. 4. Same after 40,000 reversals. × 150.

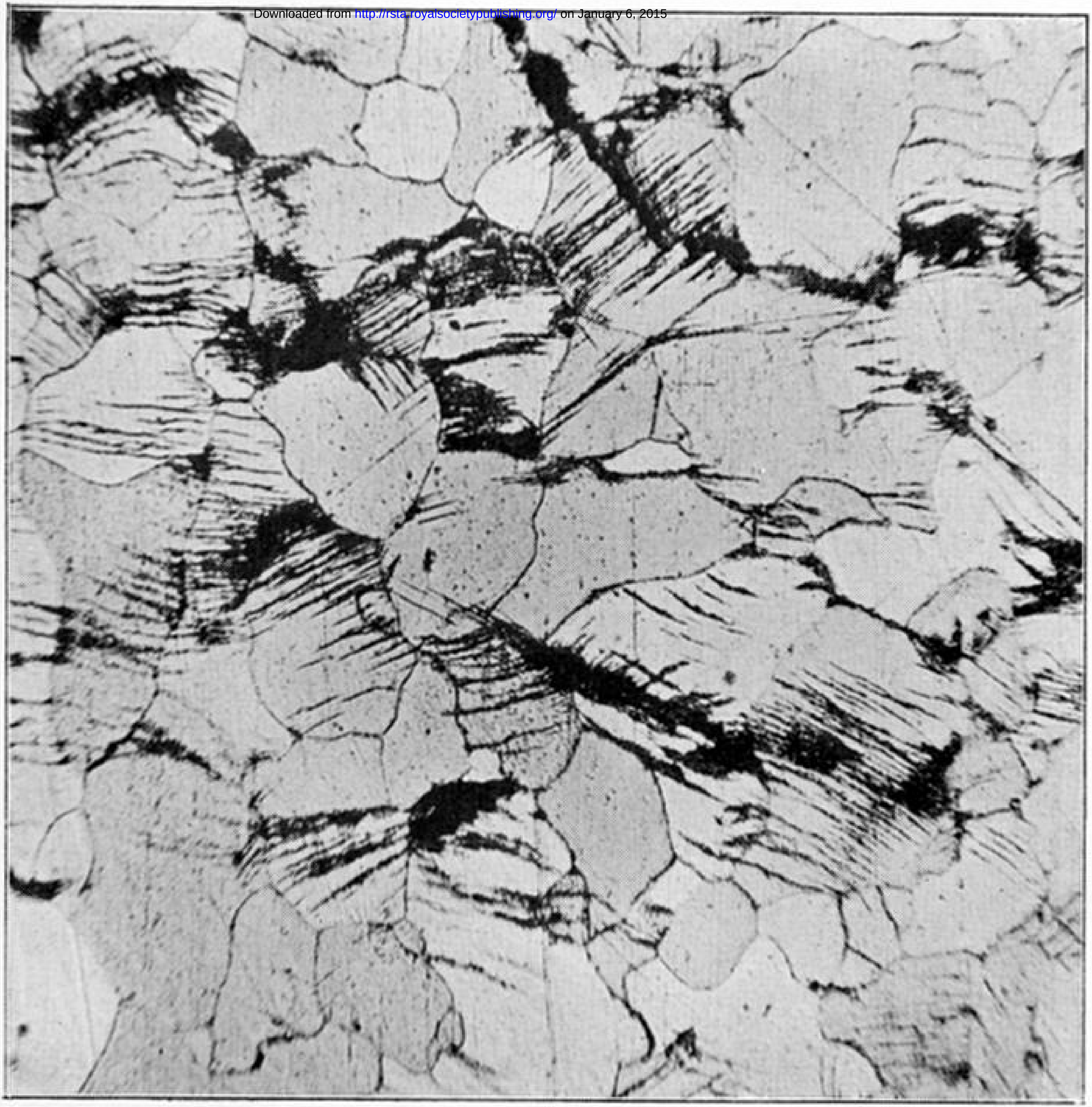

Fig. 5. Same after 60,000 reversals. × 150.

Fig. 6. Same after 70,000 reversals and re-polishing and re-etching. × 150.

Fig. 7. Specimen after 170,000 reversals of a stress of 12·3 tons per sq. inch. × 150.

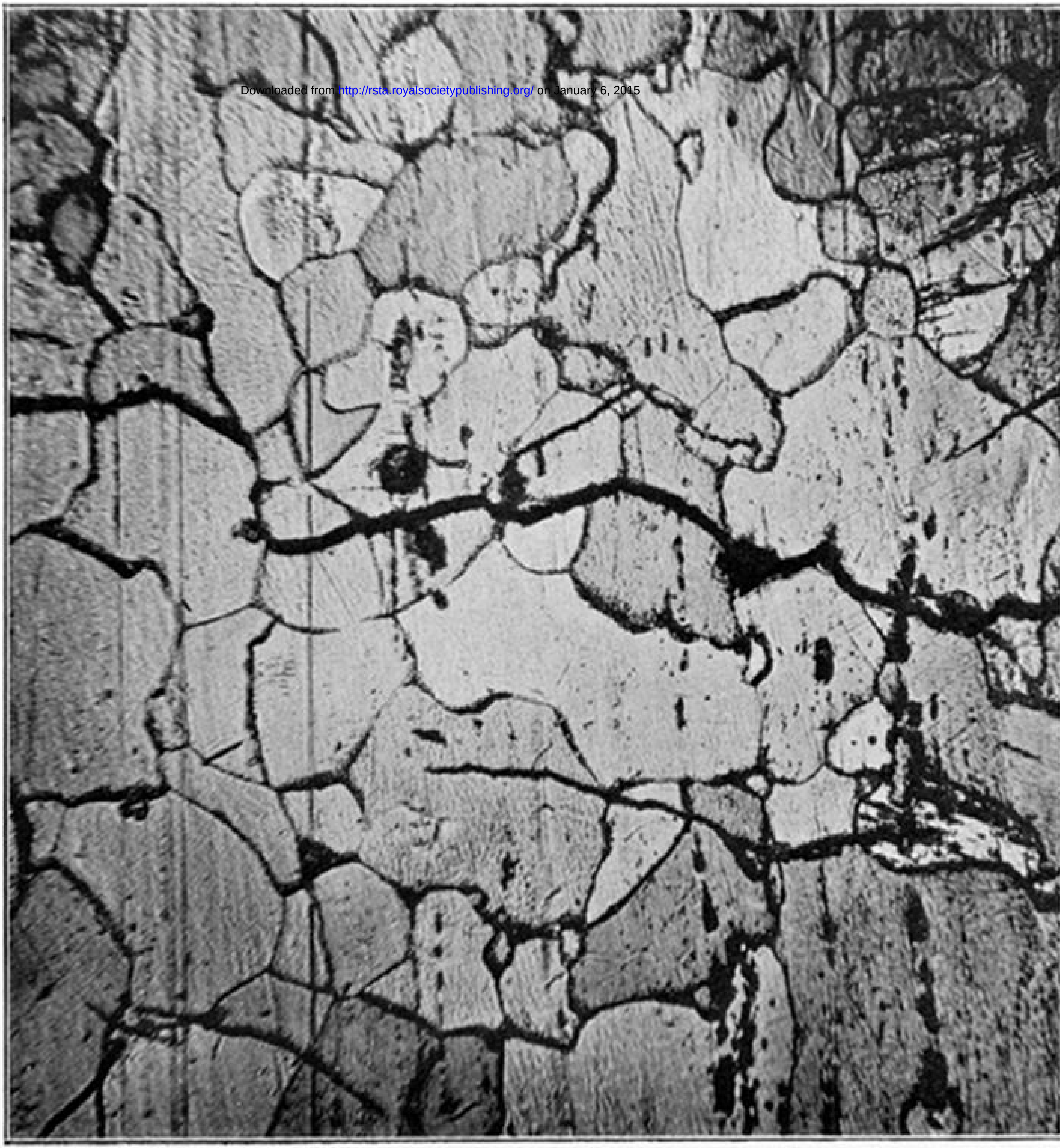

Fig. 8. Same after re-polishing and re-etching. × 150.

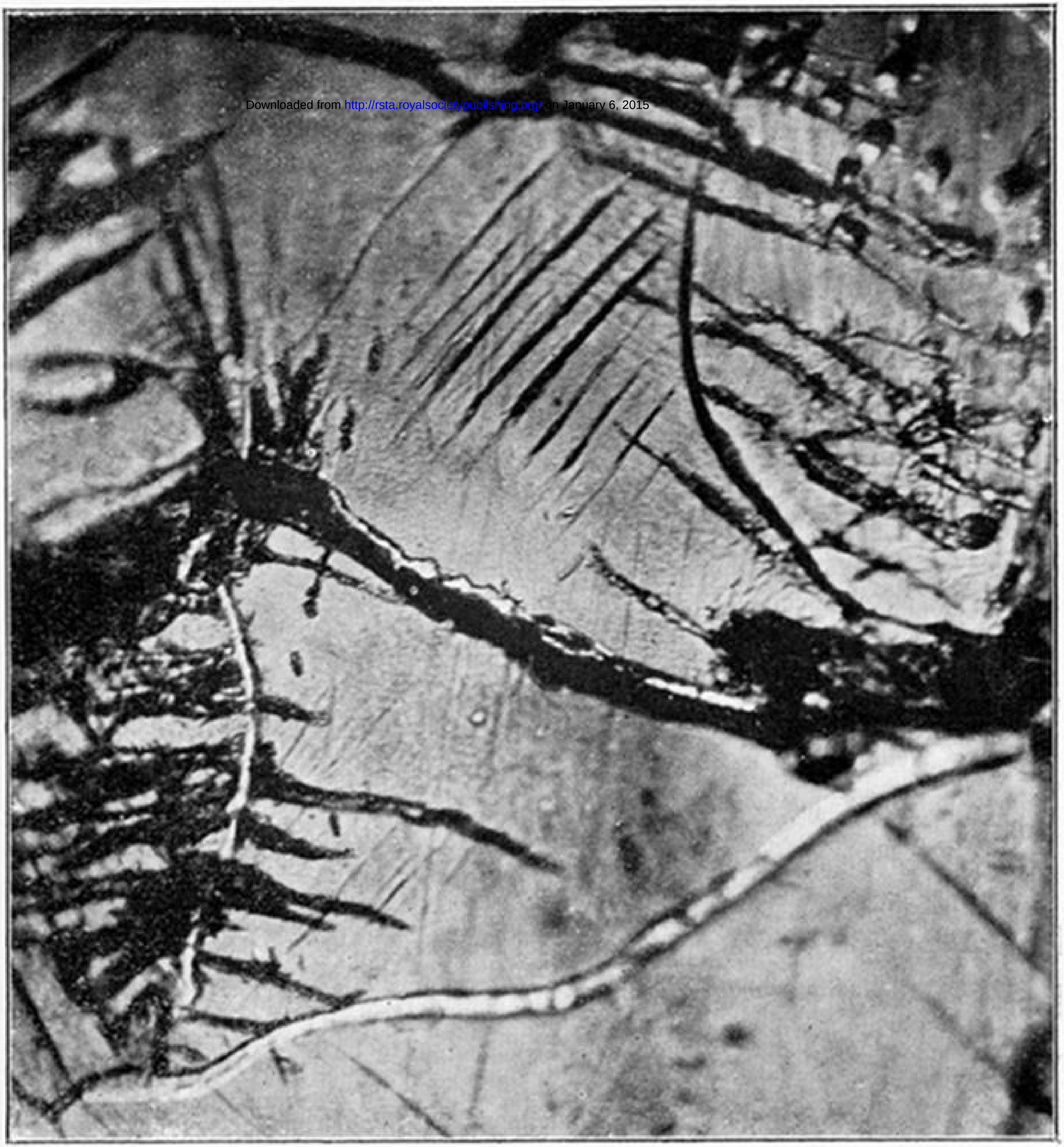

Fig. 14. Another part of the specimen of figs. 9–12, after 160,000 reversals. × 1000.

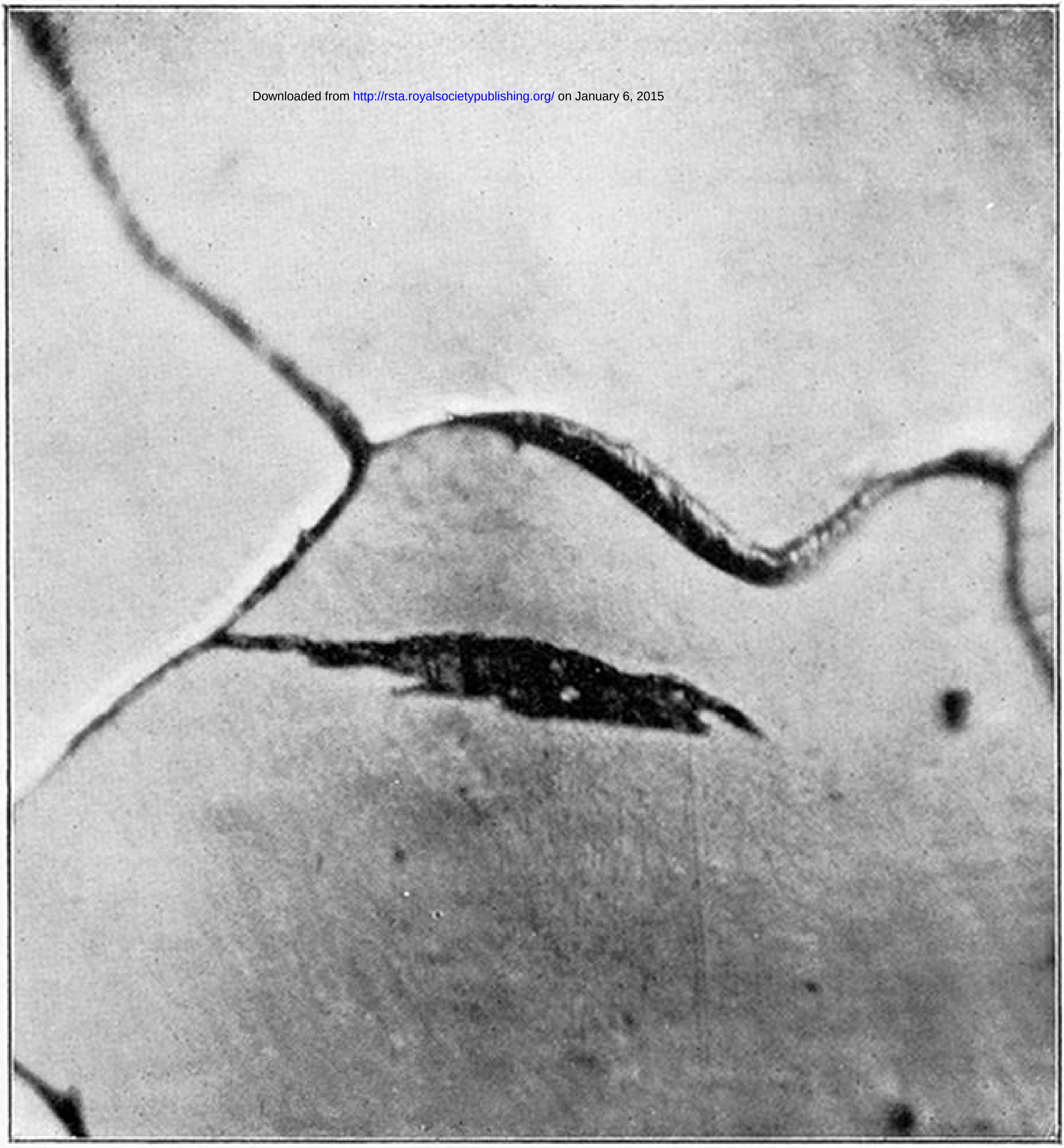

Fig. 15. Specimen after 3,000,000 reversals of a stress of 6·9 tons per sq. inch. × 1000.

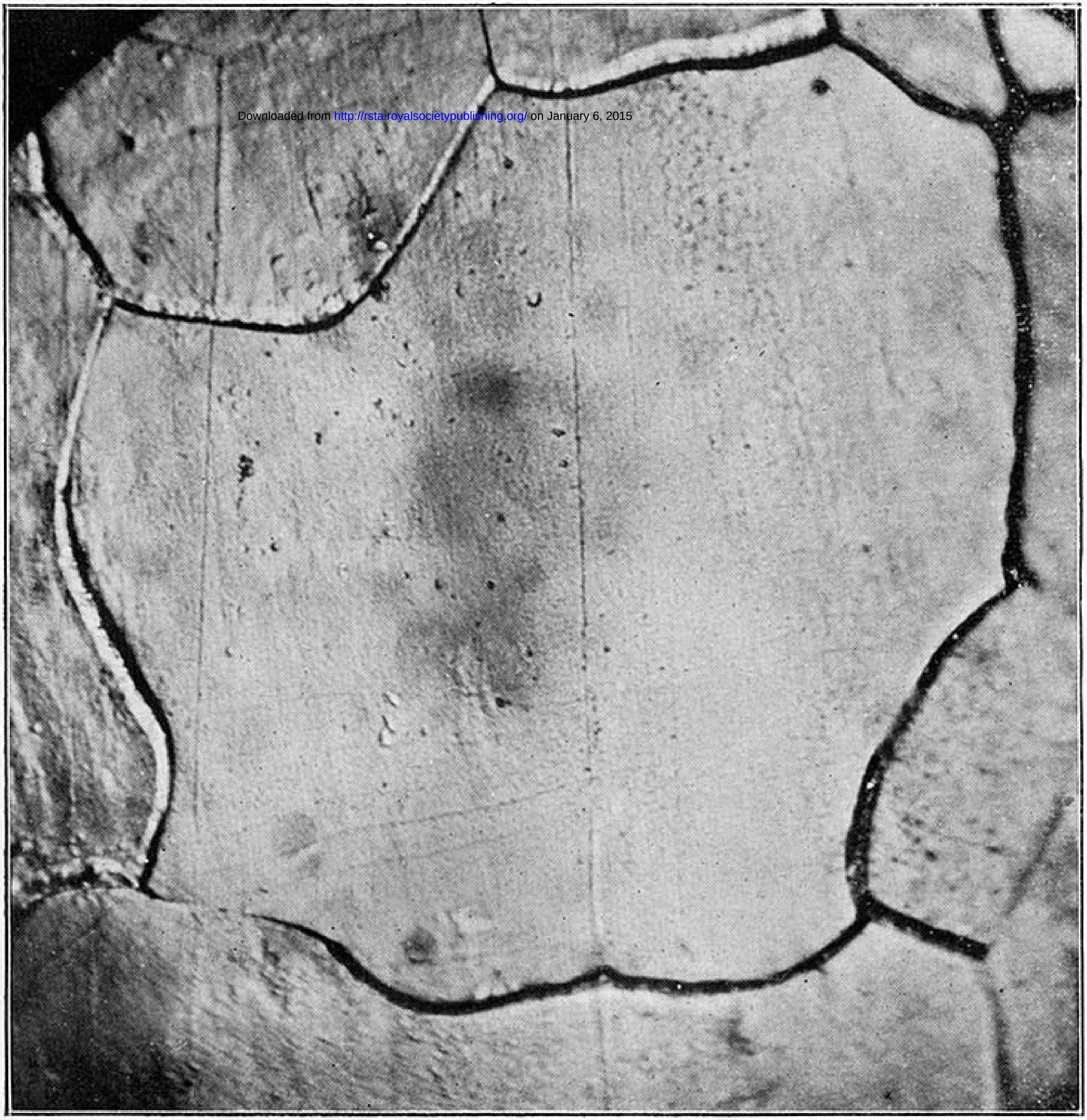

Fig. 9. Specimen after 1000 reversals of a stress of 12·4 tons per sq. inch. × 1000.

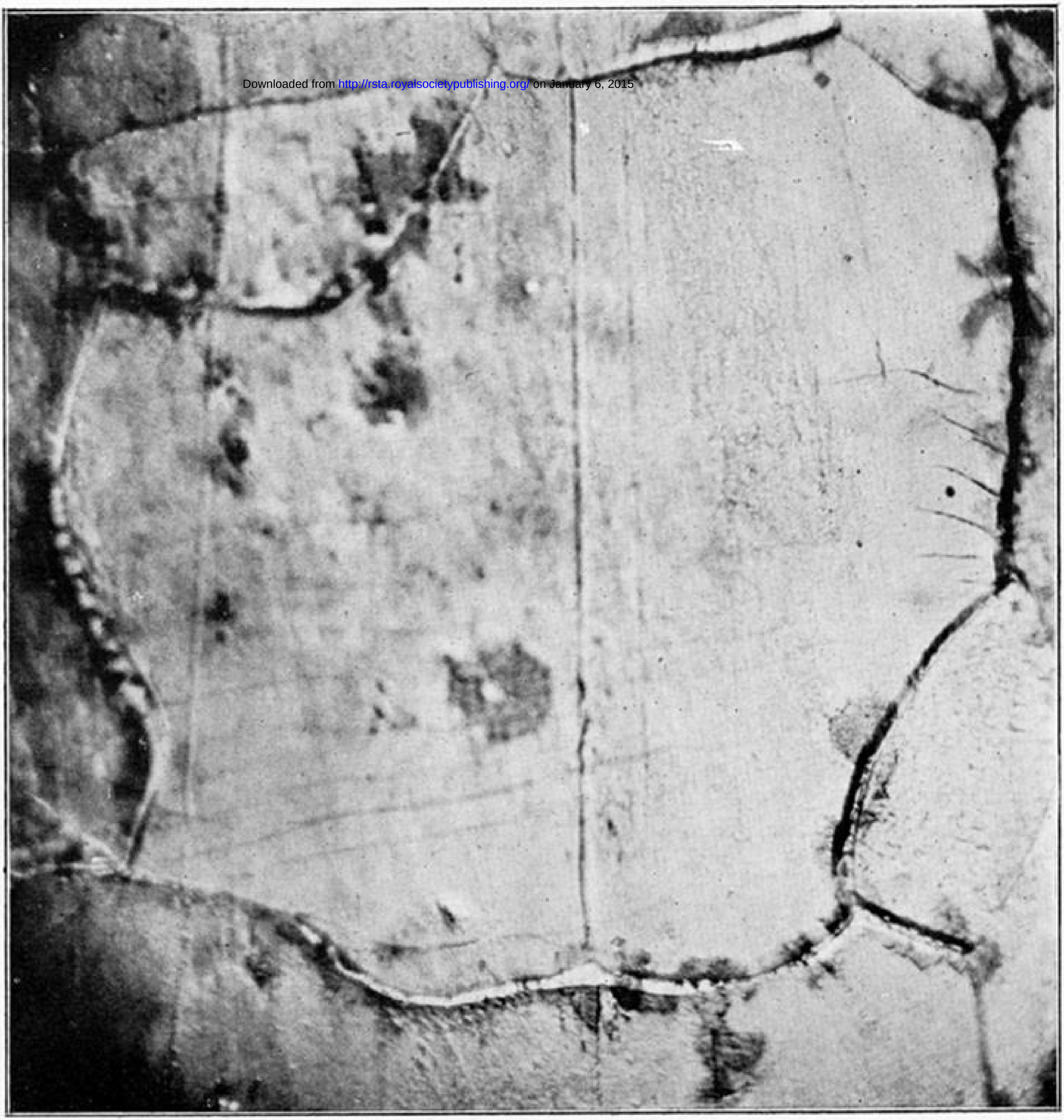

Fig. 10. Same after 2000 reversals. × 1000.

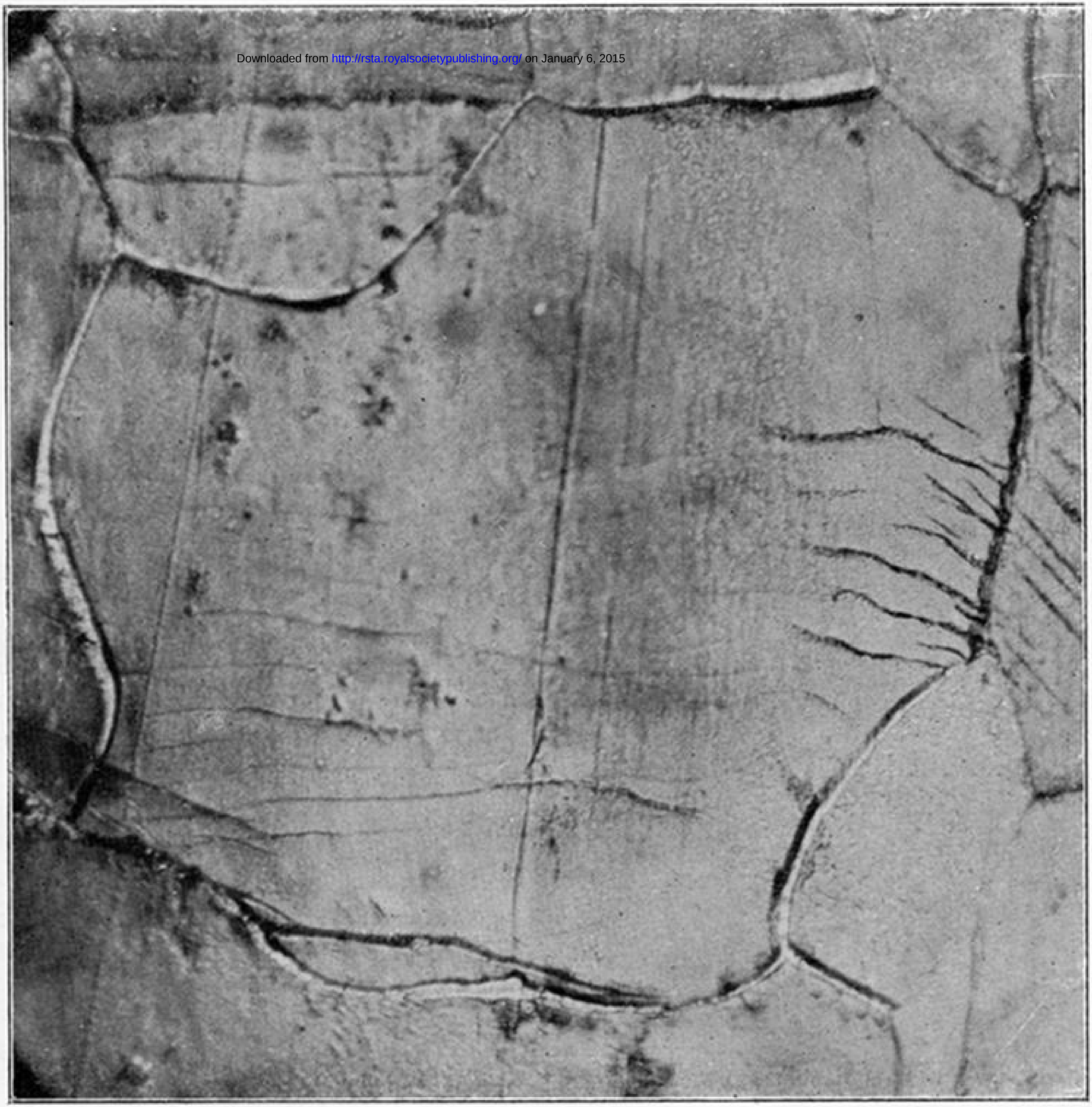

Fig. 11. Same after 10,000 reversals. × 1000.

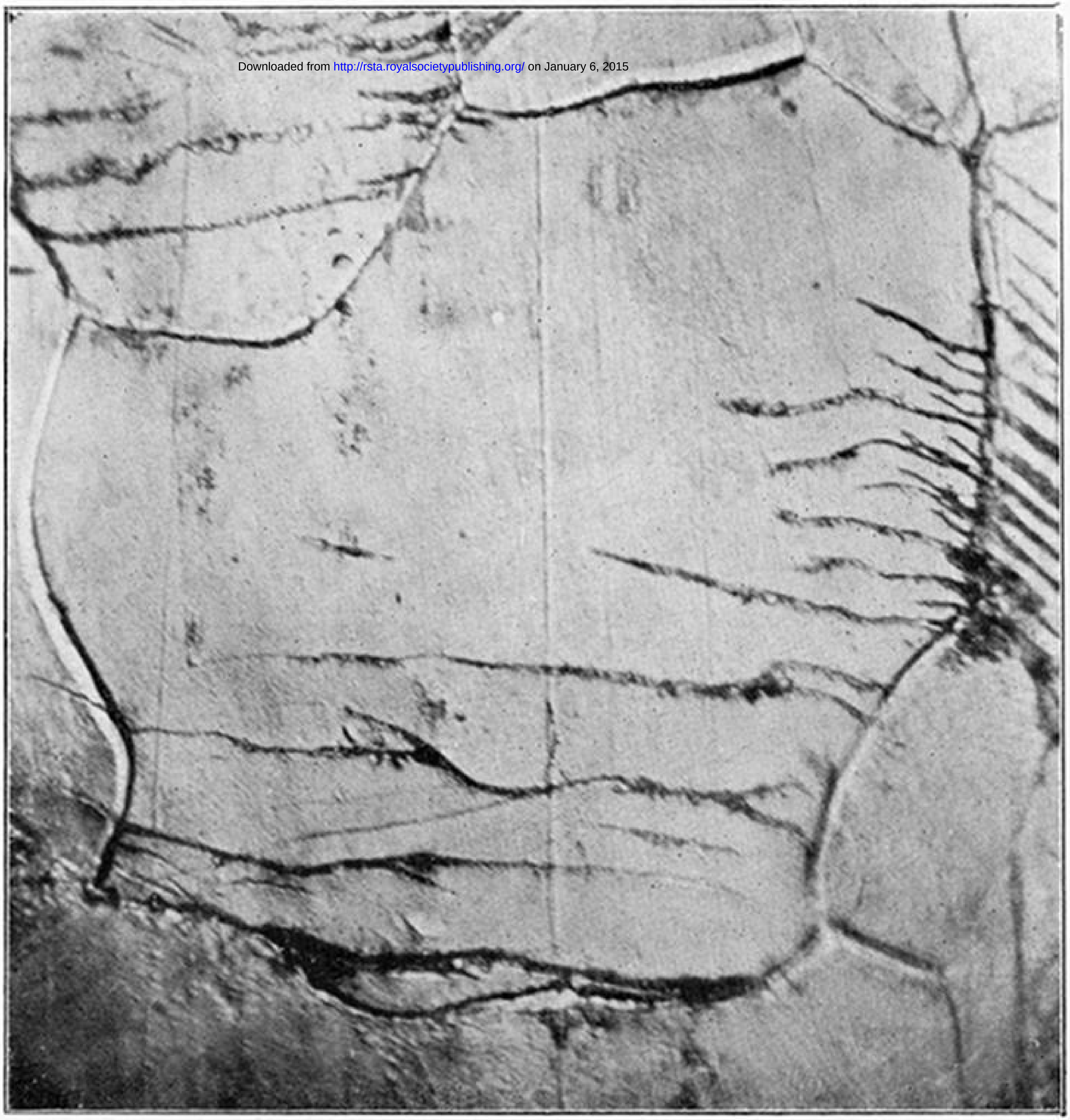

Fig. 12. Same after 40,000 reversals. × 1000.