

PHOTOMICROGRAPHS OF STEEL AND IRON SECTIONS AT HIGH MAGNIFICATION.

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Owing to the importance of the study of Microstructure much attention has been given to this subject since the days when the late Dr. H. C. Sorby, F.R.S., of Sheffield, originated, in 1857, this method of examining structures of various materials, including Iron and Steel. Indeed, one of the most striking features of the progress of Metallurgy in recent years is the great development of the use of microscopical methods of investigation. We submit some photomicros, Figs. 1 and 2, Plate A, representing some of the early work of Dr. Sorby at 9 magnifications. We also submit as a comparison, and in order to demonstrate the great advance in Metallography, Photomicrographs Figs. 3 to 25 showing later work of the writers of this Paper, in which magnifications are dealt with of 100 and up to no less than 8,000.

In carrying out this work, our best thanks are due to Mr. H. Wrighton, B.Met. for the assistance he has rendered and for the care and skill he has exercised in preparing the Photomicrographs accompanying our Paper.

One of us well remembers his conversations with Dr. Sorby regarding the micro study of his own early specimens of Manganese Steel, in 1883-1887. Dr. Sorby never turned away the youngest enquirer, and he little imagined when first describing his method in 1857 what an important aid this would eventually prove to Metallurgy. This is another instance of the great value to the Metallurgist of original work by the pure Scientist. Next to Sorby, this important branch of investigation owes more for its development to Arnold and Osmond than any others. It has been further advanced by Sauveur, Stead, Le Chatelier, Carpenter, Howe, Martens, Robin, Rosenhain, and many others.

Sorby bequeathed £15,000 to the Royal Society for the establishment of a Fellowship for the carrying on of original Scientific Research, the object specified being "to promote the discovery of new facts rather than the teaching of what is known," and stated that as far as possible the Researches should be carried out at the University of his own native City, Sheffield. To this Englishman, Sorby, the whole world has fully and freely given the credit of originating this important form of research which enables the structure of Iron and

its Alloys, including in that term the material generically known as "Steel," to be examined and understood in a manner which was before not possible. "Steel" is a wide term and to-day covers material which is practically pure Iron, for example, products containing 99.9 per cent. of Iron which offer high resistance to corrosion and oxidation and containing practically no Carbon, up to the material used for wroble or drawing plates which contain even more than 2 per cent. of Carbon.

Twenty-five years ago there were scarcely half-a-dozen Steel Works in the country which could lay claim to the possession of a Microscope suitable for metallographical examination. At the present time it may be safely said that no steel works of any size is without one. Nor is the use of the Microscope confined to the examination of Iron and Steel sections, for those engaged in the investigation of non-ferrous metals and alloys find its aid equally useful.

The history of Metallography, short as it is, is beyond the scope of the present paper. Naturally such history to be complete would record the improvements which have taken place in the construction of Lenses for metallographic work. One of the most important of these was the introduction of the Apochromatic Objective by means of which increased resolution was obtained, an absolute necessity for successful high power photomicrography. Unfortunately, as this Country had occasion to find out on the outbreak of War, the making of these objectives has in the past been largely in foreign hands. Steps are being taken to remedy this, and there is every reason to hope that here, as in other directions, in future, we shall be rendered entirely independent of the foreigner.

Great as have been the advances made in the microscopical examination of Iron and Steel, there still remains a wide field for exploration; for example, as regards methods which will enable increased magnifications to be obtained. It is wonderful what can be accomplished by the aid of the human eye alone, and even to-day the finest quality of crucible cast steel is, in its ingot form, first packed or sorted over in this manner. It is stated that an experienced workman can, by the eye, detect from the appearance of the fracture differences as small as .05 per cent. to .10 per cent. of Carbon. No doubt for many purposes an ordinary strong magnifying glass will tell much and more than the unaided eye can do, but when it is desired to reveal structures minutely, then the microscope is called in with great advantage. Magnifications of 10 or less, upwards to 1,000 or 1,500 are those most commonly used in metallography. Photomicrographs of larger magnifications than 1,500 have been rarely published. The Authors have, however, carried out experiments in order to obtain photographs of 5,000 and even 8,000 magnification, which may be of interest to this Society.

The very fine structures met with in alloy steels have made it desirable and induced the Authors to prepare in their research photomicrographs at higher magnifications than have hitherto been obtained. With great care and attention to necessary details, particulars of which are described in this Paper, we have been able to

obtain photographs of Iron and Steel sections at the high magnification of 8,000 diameters. To give an idea of what this means, it may be mentioned that the diameter of the actual field shown in a $3\frac{1}{4}$ " circle photograph at this magnification is only .00041" or $1/2460$ ". The actual area of this field examined is .00000013 square inches. The polished section under micro-examination is usually about $\frac{1}{4}$ in. square. If the whole of this area were magnified 8,000 times it would yield a square about 55 yards by 55 yards, occupying an area of approximately 3,000 square yards, that is to say, not far away from three-quarters of an acre.

As is well known, the modern Microscope consists of two systems of lenses, the objective and the eye-piece. The objective gives an enlarged image of the object, and the eye-piece further magnifies this image. The high power photomicrographs given in this Paper are simply high magnifications by means of the eye-piece and extra camera extension of the image given by a 2 mm. objective, or in the case of the 8,000 magnifications by a 1.5 mm. objective. Whatever may be the quality of the image given by the objective—for example, as regards resolution—that quality is reproduced in the magnified image of the eye-piece. Thus, if the objective gives a blurred image, the blur is simply magnified. In other words, it is just as though a lantern slide were projected on the screen; if the slide is a good one we get a good picture, but if bad the picture will be no better because it is magnified. The essential aim, therefore, is to get a very clearly resolved image. This needs a special quality or virtue in the objective, and this virtue is called its resolving power.

For photomicrography at high magnifications, it is specially essential that an objective of high resolving power should be used. The effect of magnification without resolution is well illustrated by Figs. 3, 4 and 5 on Plate B. These photographs are all at 600 magnifications, but taken by objectives of low, medium, and high power respectively. In No. 3 the dark ground mass is left unresolved. No. 4 shows some resolution of this dark ground mass, but in No. 5 it is practically completely resolved into its two constituents, Ferrite and Cementite in lamellar form. In the course of a search for a really good 2 mm. oil immersion objective, for photomicrographic research, we found that results obtainable with a moderate Achromat, compared with those obtained with a good Apochromat, showed differences at least as great as is illustrated in Figs. 4 and 5.

An illustration of the microstructure of an Annealed Alloy steel, containing .84 per cent. Carbon and 1.12 per cent. Chromium, is shown at four different magnifications in Figs. 6, 7, 8, and 9 on Plate C. Although the resolution of the structure is the same in Figs. 7 and 8, because the same objective was used in each case, the effect of the increased magnification is to show in a striking manner the alternate white and dark constituents of the lamellar pearlite. This effect is further emphasised in a photograph of the same section at 8,000 magnifications, shown in Fig. 9. There is no doubt that this magnification taxed the lens somewhat beyond its capacity; however, the photograph is certainly a good one and worth including, if only to show the limit obtainable with the apparatus available at the present time.

Photomicrographs of Diatoms at 5,000 magnifications and over, taken by transmitted light, have been published; but so far as we are aware steel sections at such a high magnification have not been available. This may be easily accounted for by the difficulties in the way. Although, unfortunately, we are unable to indicate an easy path by which these difficulties may be avoided, we propose to show the means by which we endeavour to overcome them.

We have already laid stress on the need for an objective of high resolving power capable of giving good definition when combined with a properly compensated eyepiece of high magnifying power.

Probably the next most essential point is that the specimen to be photographed be properly etched. Deep etching is fatal; it causes pits and furrows in the surface of the piece which extend beyond the range of depth of focus, which with a high power objective, is naturally very limited. Therefore the most delicate etching is necessary, and this we find is usually best obtained with 5 per cent. Picric Acid in Alcohol.

The illumination of the specimen for photography is the next subject for attention. For high power photography the lighting should be as intense as possible. We use a 20 ampere arc lamp of the hand fed type, and this is found preferable to one mechanically fed. It is simple, has no mechanism to get out of order, and the carbons are not liable to re-adjustment at the critical moment, just when the plate is being exposed. Moreover, mechanically fed carbons are never so firm and free from vibration as those of the hand fed types. Alternating current at about 70 volts can be used with perfect success on a 20 ampere hand fed lamp, if cored carbons are used. This is a point on which emphasis should be laid, for the makers of our apparatus have always laid stress on the necessity for direct current for photomicrographic work. Tungsten Arc and Mercury Vapour Lamps have been more recently introduced for photomicrographic work, but we have had no opportunity of testing them.

The vertical illuminator attached to the Microscope should be a plain glass disc. We find a prism unsatisfactory for this work. The light should be focussed on the diaphragm of the vertical illuminator, and of course it must be perfectly central with the Microscope and the camera.

The iris diaphragm of the illuminator should only be closed as much as is necessary to get sufficient of the field sharp. Further closing of the diaphragm not only interferes with the resolution, but produces false images. An example of this effect is shown in Figs. 10 and 11, Plate D. Fig. 10 illustrates the result produced by closing the diaphragm too much, and Fig. 11 shows a correct image obtained by proper adjustment.

The diaphragm in the condenser system should be closed so that only the area to be photographed is illuminated.

For apochromatic objectives, a blue screen as a light filter should be used, and ordinary photographic plates. The specimen is focussed first of all on the ground glass screen of the camera, and finally adjusted

with the clear glass screen and the aid of the focussing magnifier. There is one point that has not been mentioned, which is quite obvious, and that is the necessity that the mounting of the whole photomicrographic apparatus should be perfectly rigid and free from vibration.

We have selected a few photomicrographs in order to show the effect of increasing magnifications on the same section, and also to illustrate well-known types of microstructure at high magnifications. The objectives used in obtaining photographs at 1,500 and over are stated on the plates.

The photographs on plates A, B, C and D have already been dealt with in the text.

PLATE E. — Figs. 12, 13, 14 and 15, show the microstructure of a Nickel Chromium Alloy Steel in two different conditions. Even at 1,500 magnifications the structure is seen to be very fine and close textured ; it is rather more clearly defined at 5,000 magnifications, but a structure of this kind is very difficult to photograph owing to the want of contrast obtained even with the most careful etching.

PLATE F. — Figs. 16, 17, 18 and 19 show the structure of Grey Cast Iron. The black constituent is Graphite, and the ground mass Pearlite. The four photographs on this plate illustrate very strikingly the advantage of higher magnifications in order to see clearly the details of a fine Pearlitic structure.

An additional photograph (Fig. 19a) is given on Plate F, which has been obtained by making an enlargement of the negative from which Fig. 18 was obtained. The enlargement has been so adjusted that its magnification is 5,000 ; a comparison is therefore obtainable with that of Fig. 19, which has been obtained by the direct method. There does not appear to be much to choose between the two Photographs in this instance, but in the case of more complicated subjects such as those illustrated in Figs. 20 to 22 on Plate G, the direct method of photomicrography, although very much more difficult than the indirect one of enlargement, is far preferable to the latter because the choice of field to be photographed is made at high magnification—an important advantage.

PLATE G. — Figs. 20, 21 and 22. Photographs 20 and 21 show the microstructure of a Carbon-Chromium steel in two different conditions, magnified 8,000 diameters. The former is a Sorbitic Pearlite structure, and the latter consists of Martensite and Troostite (black areas). — Fig. 22 shows the microstructure of a quenched Carbon steel at 8,000 magnifications, and is Troosto-Martensite.

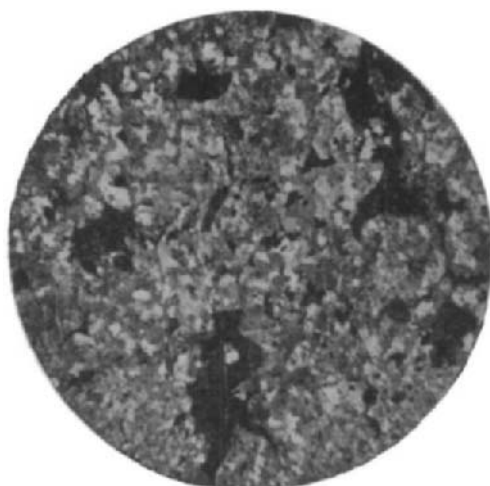
PLATE H. — Figs. 23, 24 and 25. These photographs show the microstructure at 5,000 magnifications of a steel containing 1.41 per cent. Carbon in three different conditions. Fig. 23 is a typical Pearlite and Cementite structure ; Fig. 24 a Martensitic structure, and Fig. 25 a structure of mixed Troostite and Cementite.

The value of higher magnification especially as illustrated in Figs. 8, 9 and 19 can be emphasised as a result of this research. These Photographs at higher magnifications show in a striking manner the details of a structure which at lower magnifications are only

PLATE A.

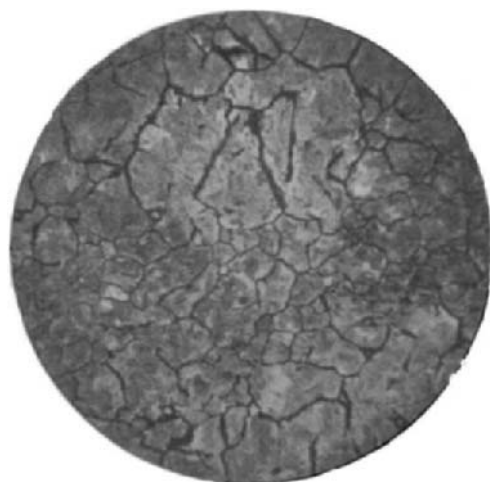
Examples of early Photomicrographs from Sorby's Paper to the Iron and Steel Institute, 1887, "On the Microscopical Structure of Iron and Steel."

FIGURE 1.



Photomicrograph by Sorby.
Magnification 9.
Hammered Bloom Carbon .05%

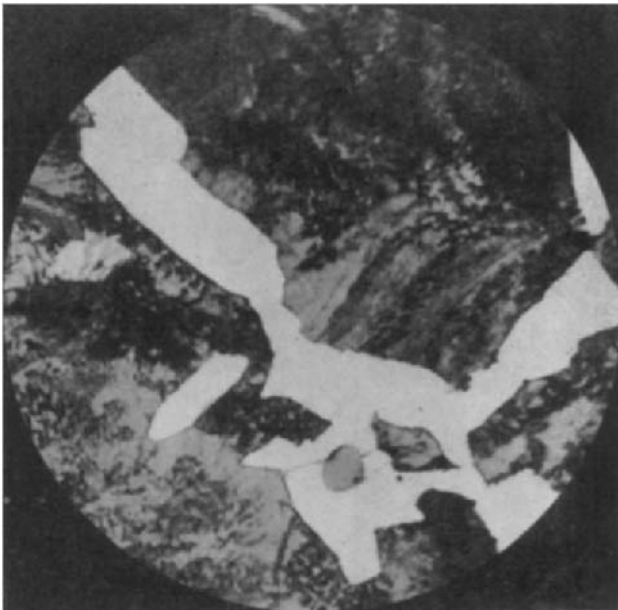
FIGURE 2.



Photomicrograph by Sorby
Magnification 9.
Blister Steel, Longitudinal Section.

PLATE B.

FIGURE 3.



Magnification 600.
12 MM. ACHROMAT.

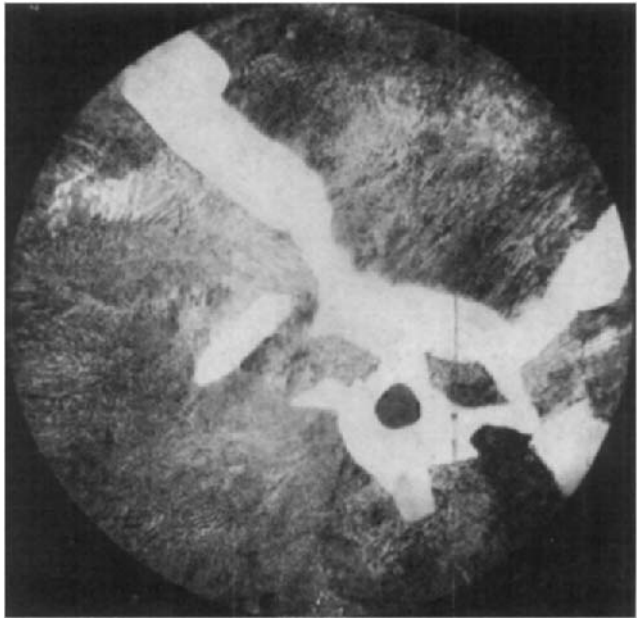
FIGURE 4.



Magnification 600.
4 MM. ACHROMAT.

Photomicrographs showing the Effect of Magnification .
without Resolution.

FIGURE 5.



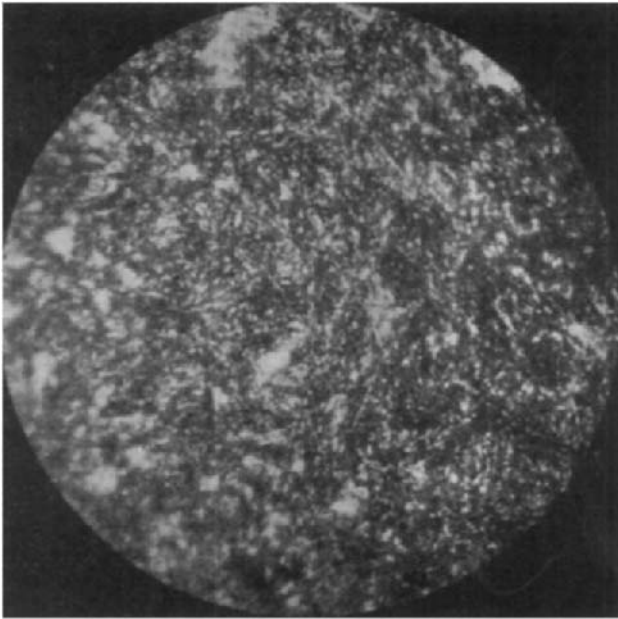
Magnification 600.
2 MM. APOCHROMAT.

The Steel used in this Experiment had the following composition:

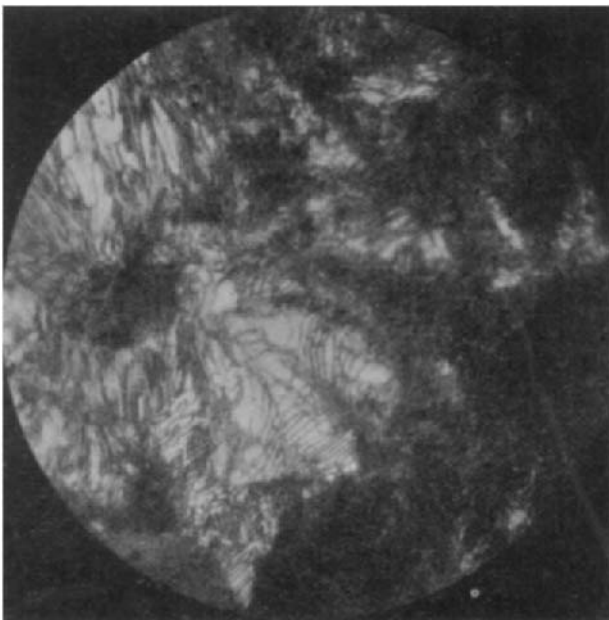
C.	Si.	S.	P.	Mn.
.48	.17	.029	.034	1.00%

Photomicrographs showing the Effect of Magnification
without Resolution.

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PLATE C**FIGURE 6.**

Magnification 100.

FIGURE 7.

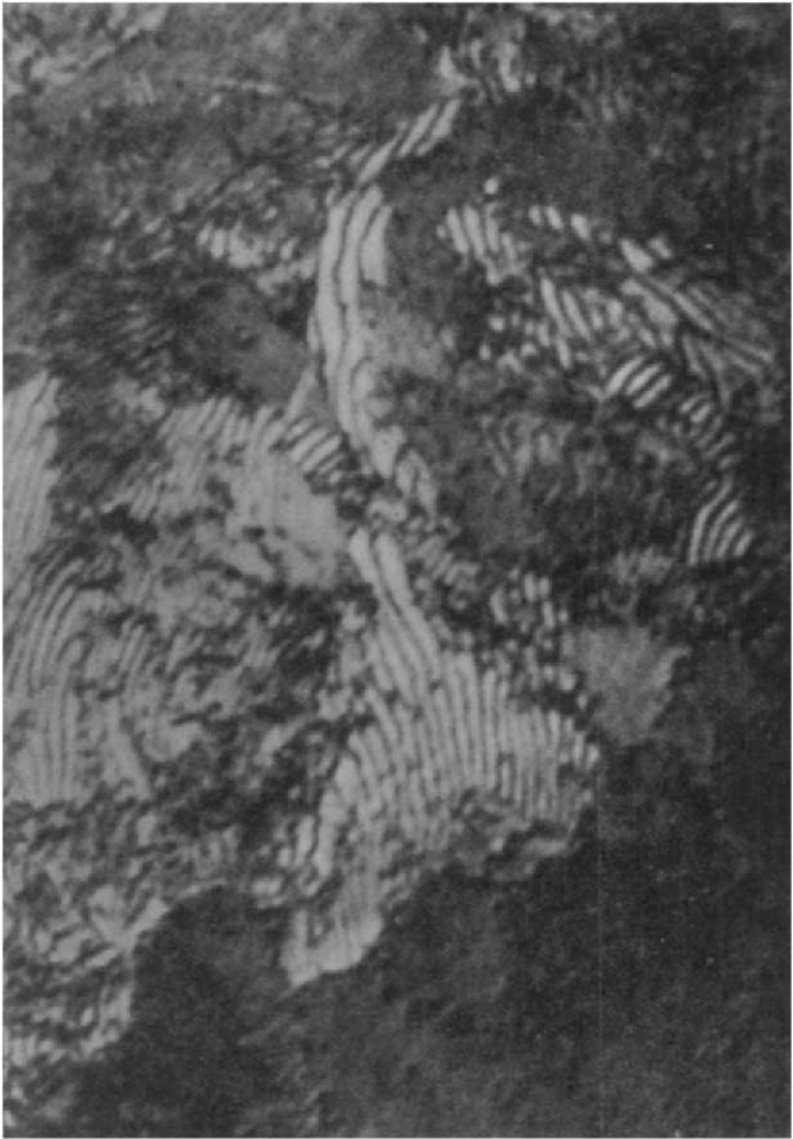
Magnification 1,500.

2 MM. APOCHROMAT STRUCTURE OF FINE LAMELLAR
AND SORBITIC PEARLITE.

The Steel used in this Experiment had the following composition:

.84	.30	.45	1.12	.12%
C.	Si.	Mn.	Cr.	Ni.

FIGURE 8.



Magnification 5,000.

2 MM. APOCHROMAT STRUCTURE OF FINE LAMELLAR
AND SORBITIC PEARLITE.

The Steel used in this Experiment had the following composition:

.84	.30	.45	1.12	.12%
C.	Si.	Mn.	Cr.	Ni.

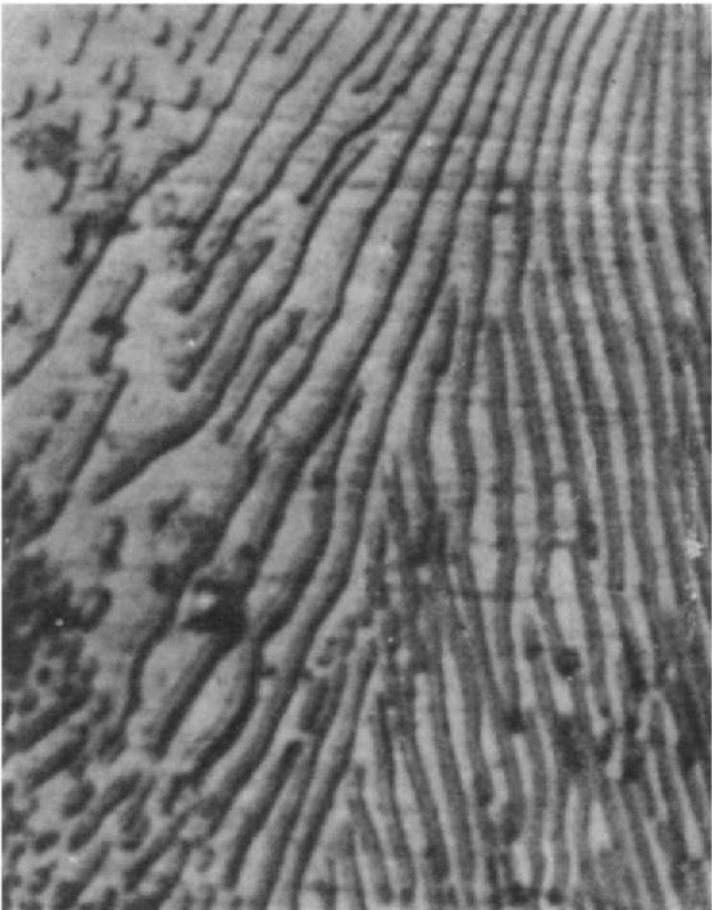
FIGURE 9.



Magnification 8,000.
1.5 MM. APOCHROMAT.

PLATE D.

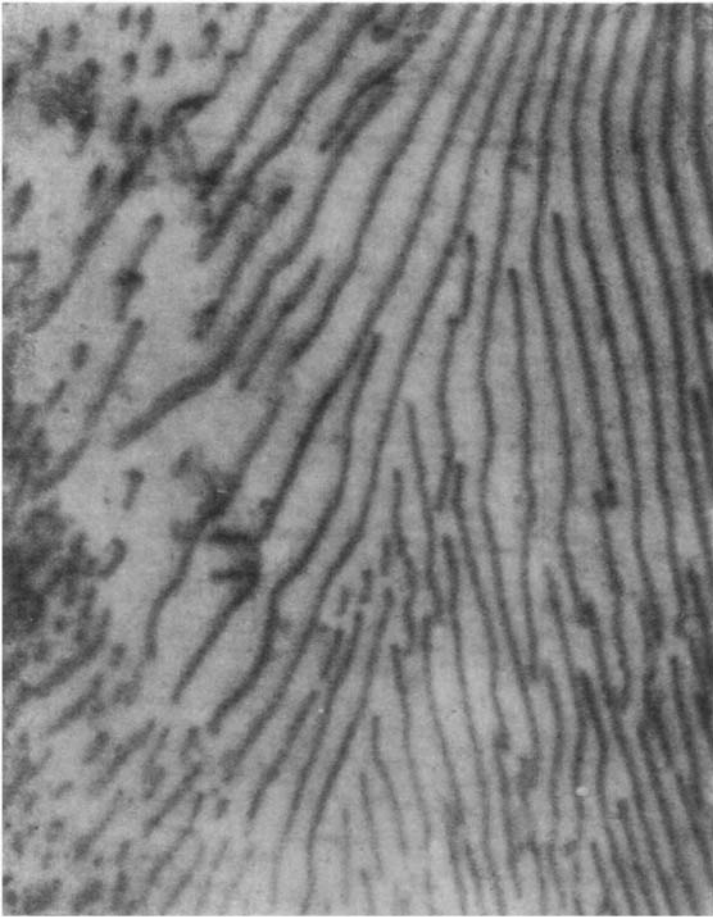
FIGURE 10.



Magnification 5,000.

Photomicrographs showing, respectively, the effect of Incorrect
and Correct use of the Iris Diaphragm.

FIGURE 11.

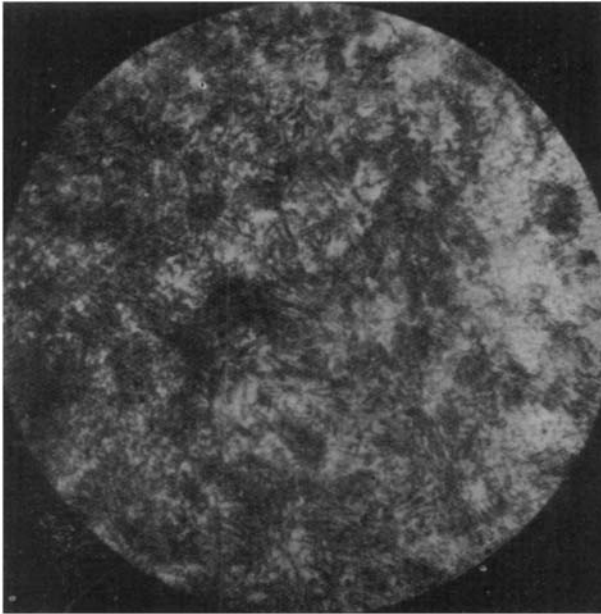


Magnification 5,000.

Photomicrographs showing, respectively, the effect of Incorrect
and Correct use of the Iris Diaphragm.

PLATE E.

FIGURE 12.



Magnification 1,500.

ANNEALED.

STRUCTURE OF FINE LAMELLAR AND SORBITIC PEARLITE

The Steel used in this Experiment had the following composition:

C.	Cr.	Ni.
.65	2.50	2.75%

FIGURE 13.



Magnification 5,000.

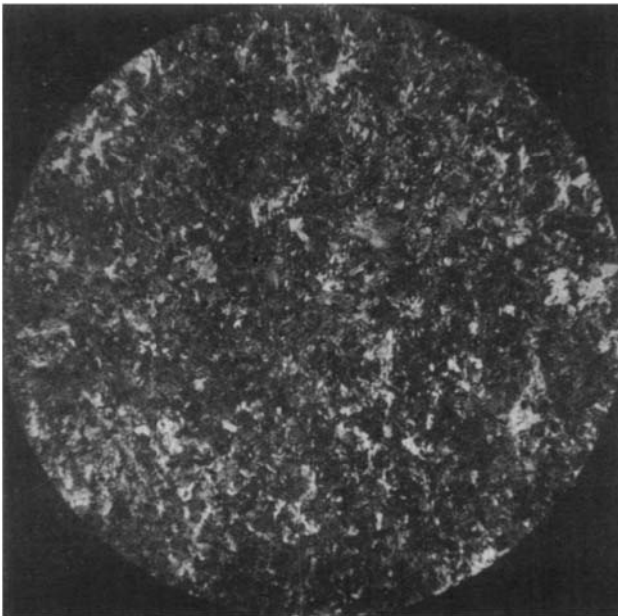
ANNEALED.

STRUCTURE OF FINE LAMELLAR AND SORBITIC PEARLITE

The Steel used in this Experiment had the following composition:

C.	Cr.	Ni.
.65	2.50	2.75%

FIGURE 14.

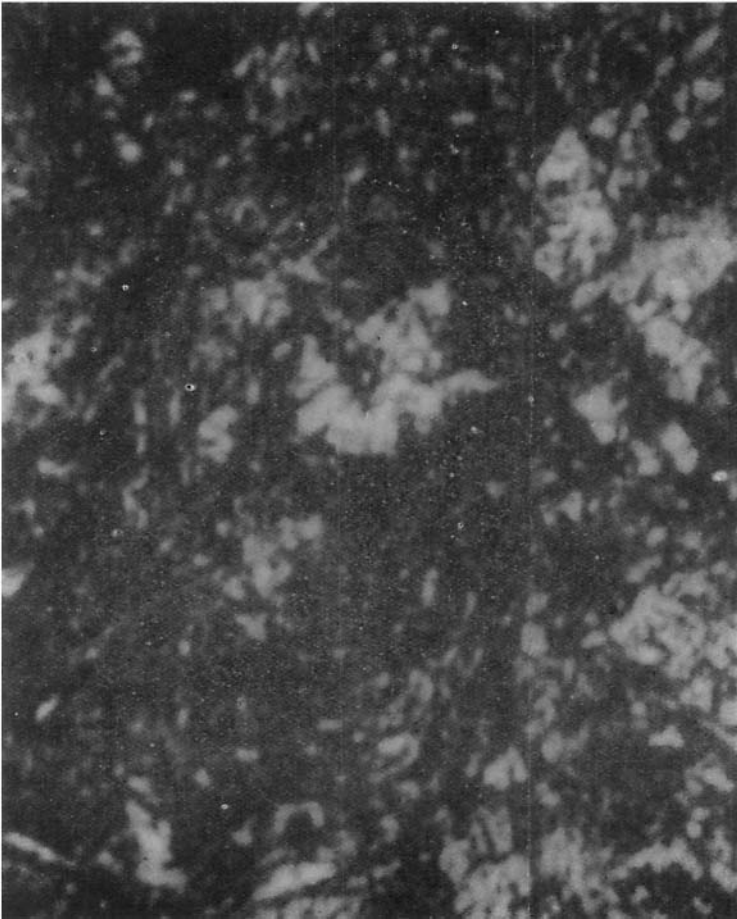


Magnification 1,500.

Quenched and Tempered.

STRUCTURE OF TROOSTITE AND SORBITE.

FIGURE 15.



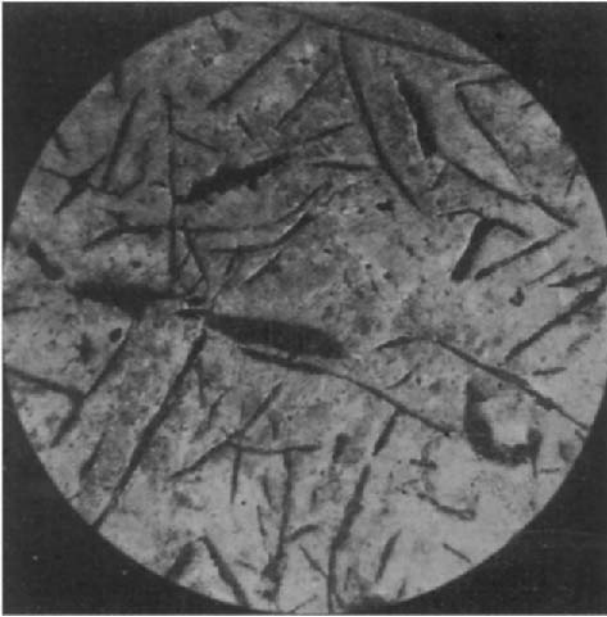
Magnification 5,000.

Quenched and Tempered.

STRUCTURE OF TROOSTITE AND SORBITE.

PLATE F.

FIGURE 16.



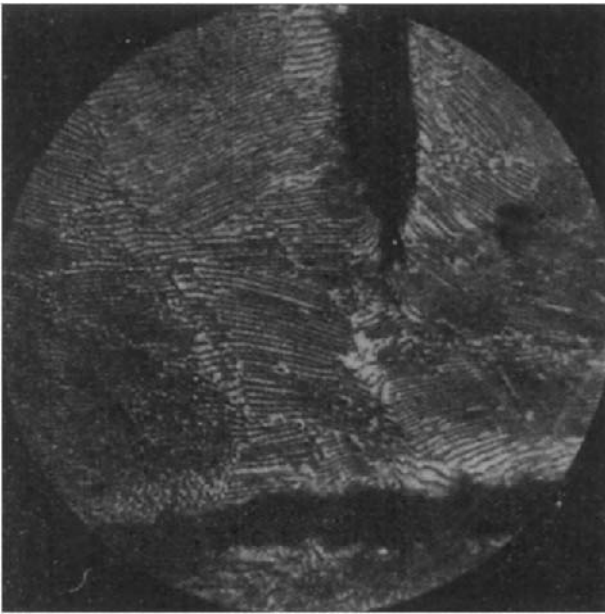
Magnification 100.

FIGURE 17.



Magnification 600.

FIGURE 18.



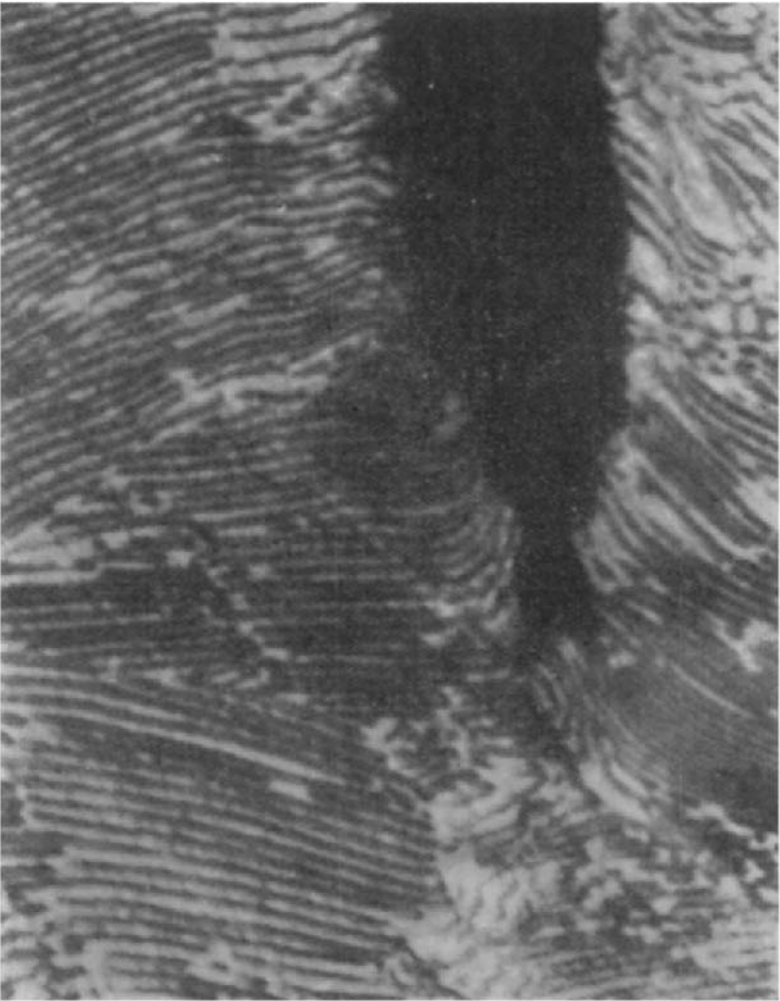
Magnification 1,500.

STRUCTURE OF PEARLITE AND GRAPHITE.

The following is the composition of the Grey Cast Iron used in this Experiment:

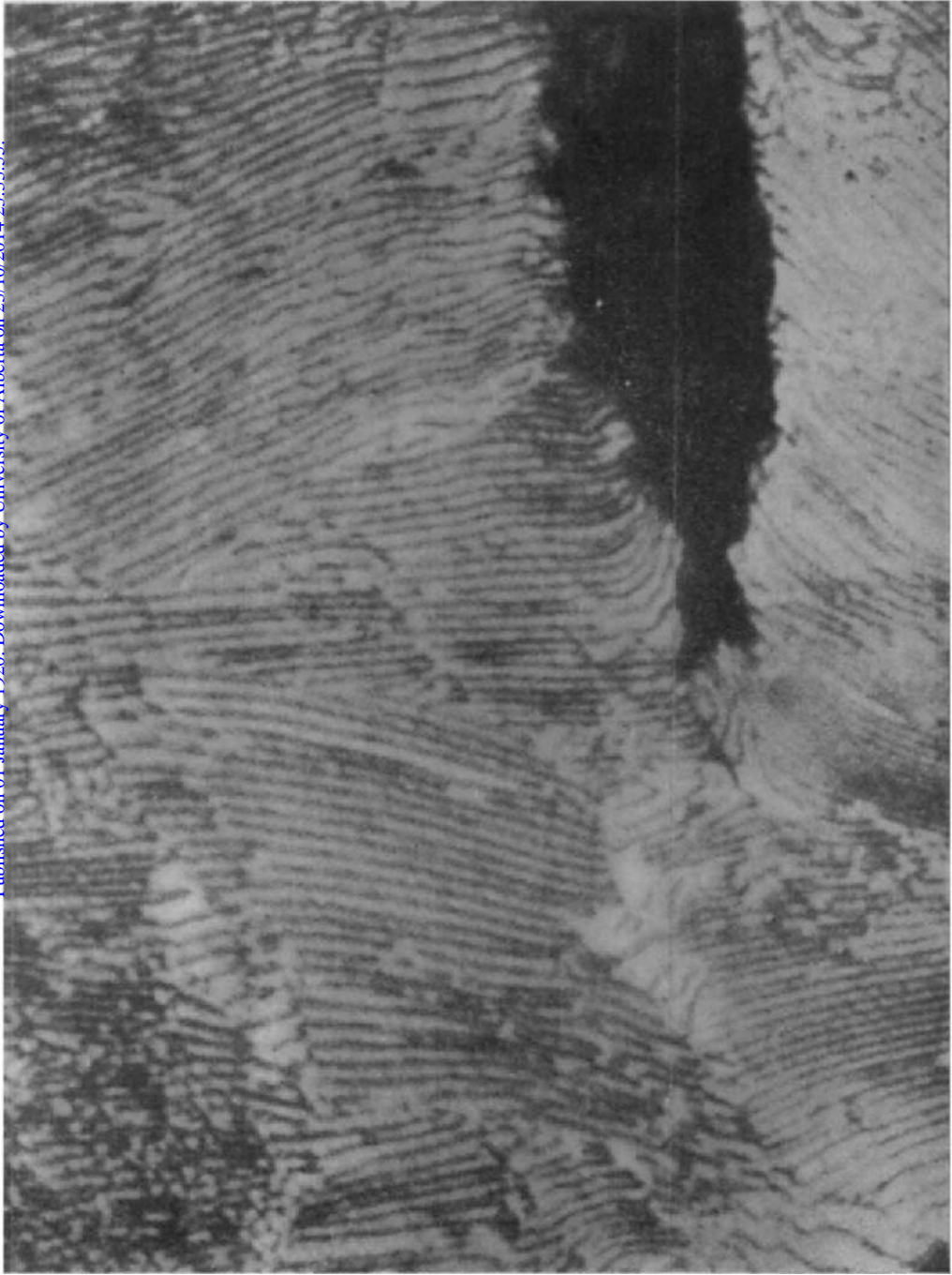
C.	Gr.	Si.	S.	P.	Mn.
3.5	2.75	2.82	.115	.28	.34%

FIGURE 19.

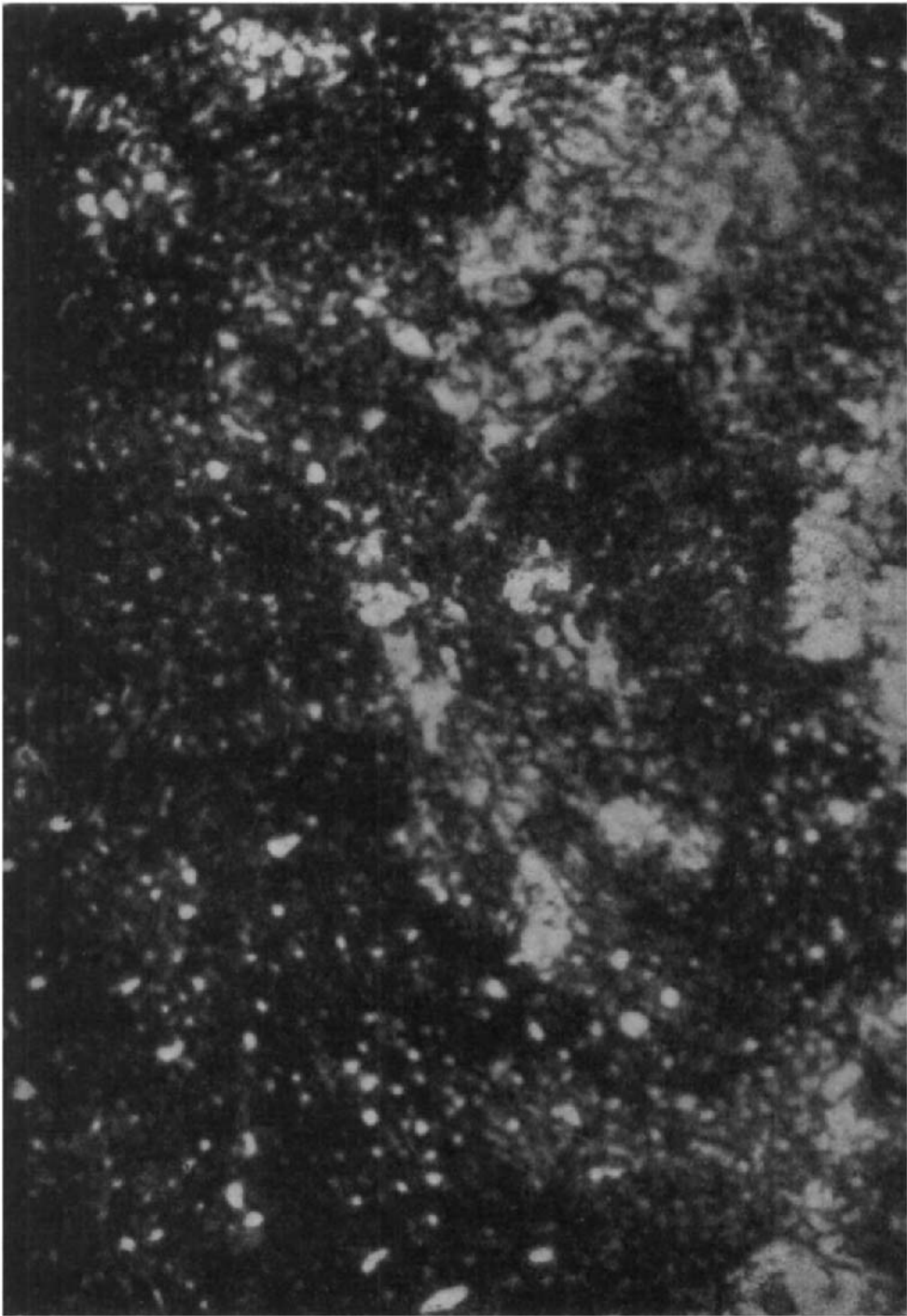


Magnification 5,000.

FIGURE 19a.



Magnification 5,000 approx.
ENLARGEMENT FROM NEGATIVE OF PHOTOGRAPH 18

PLATE C.**FIGURE 20.**

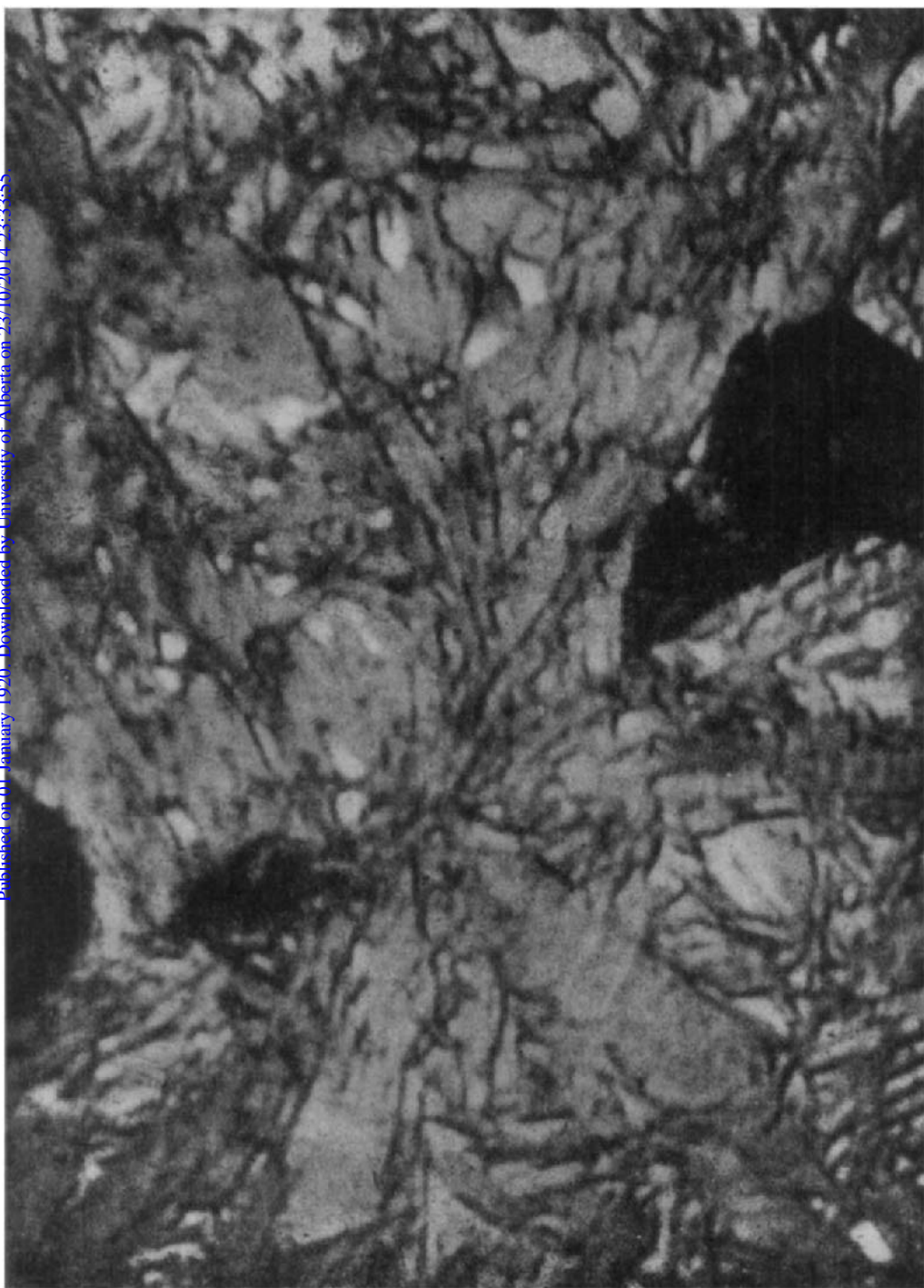
Magnification 8,000.
1.5 MM. APOCHROMAT.
SORBITE.

Quenched and Tempered.

The Steel used in this Experiment had the following composition:

C.	Si.	S.	P.	Mn.	Cr.
.03	.23	.042	.021	.31	2.51%

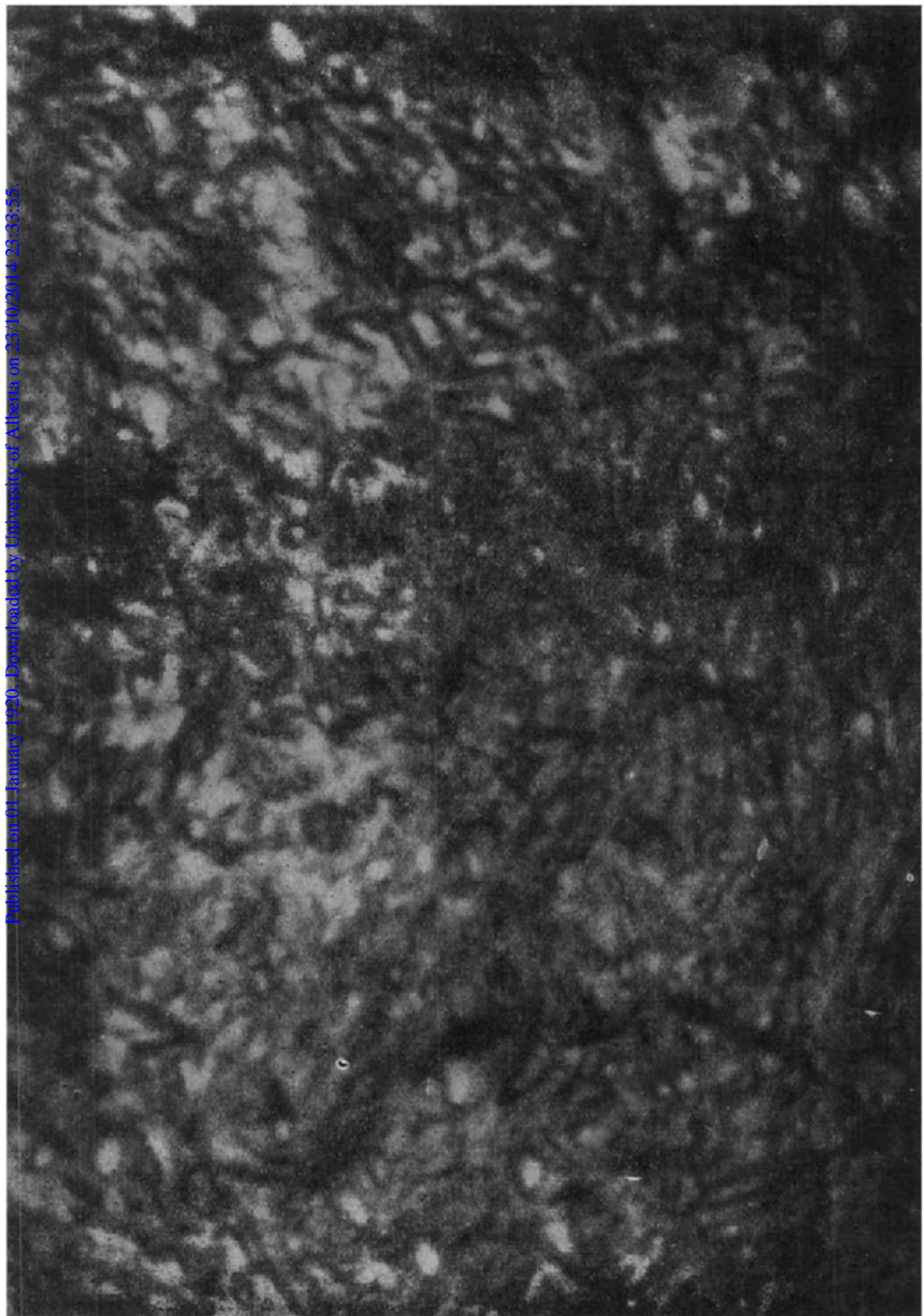
FIGURE 21.



Magnification 8,000.
1.5 MM. APOCHROMAT.
TROOSTO-MARTENSITE.
Quenched.

C.	Si.	S.	P.	Mn.	Cr.
.93	.23	.042	.021	.31	2.51%

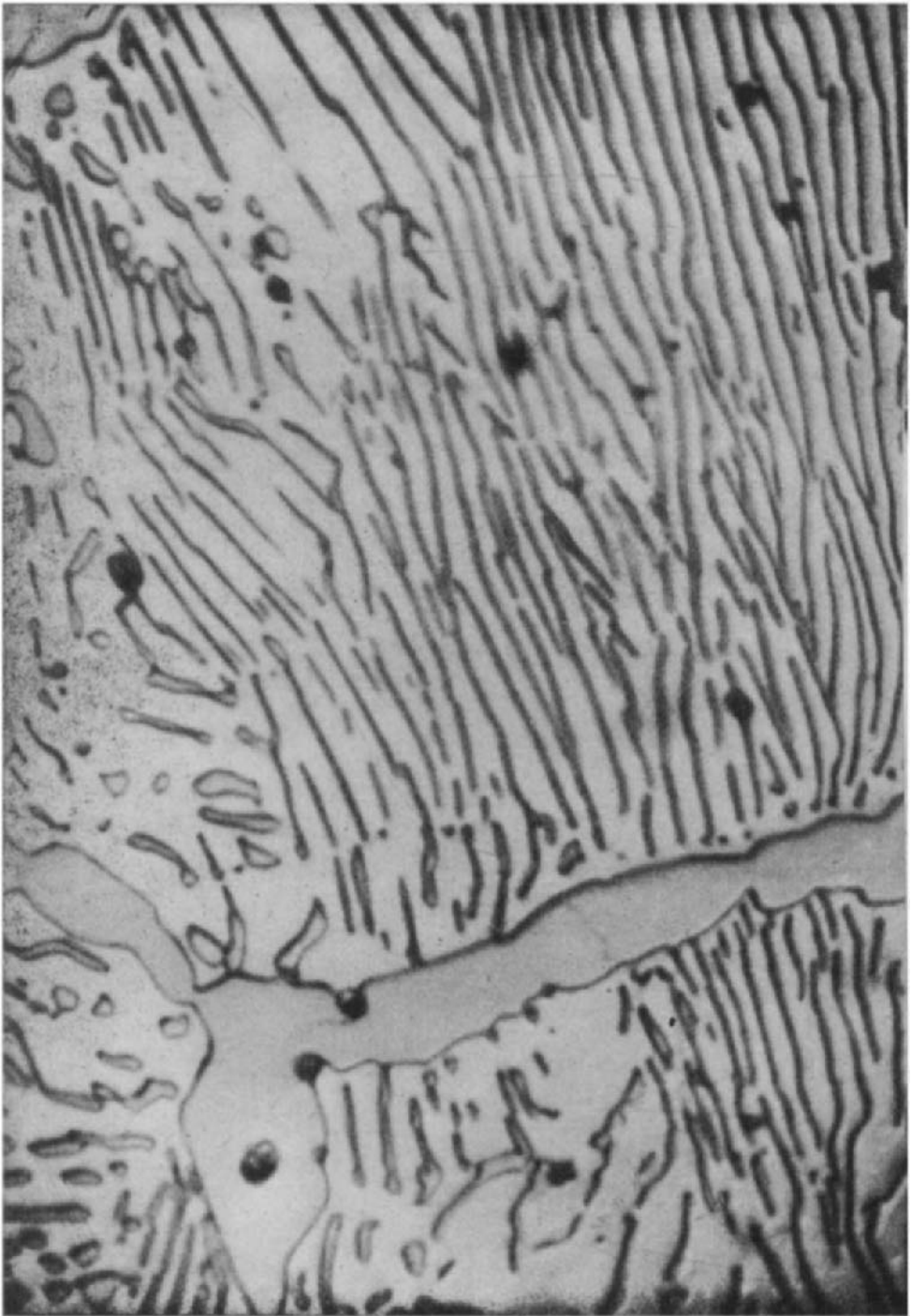
FIGURE 22.



Magnification 8,000.
1.5 MM. APOCHROMAT.
MARTENSITE AND TROOSTITE.
Quenched.
C. Si. Mn.
.90 .27 .29%

PLATE H.

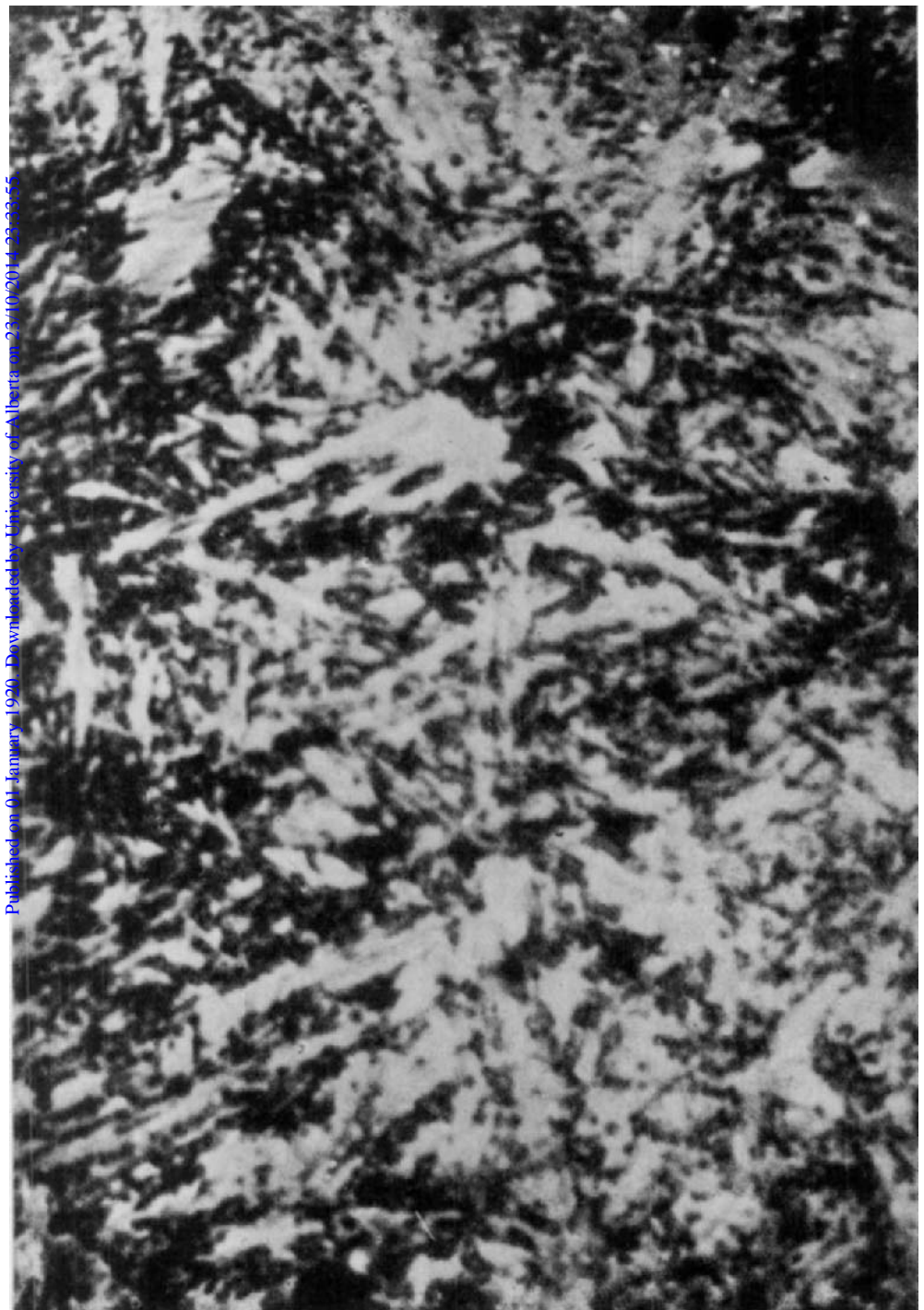
FIGURE 23.



Magnification 5,000.

1.5 MM. APOCHROMAT.

PEARLITE AND CEMENTITE.
Annealed.

FIGURE 24.

Magnification 5,000.
1.5 MM. APOCHROMAT.
MARTENSITE.

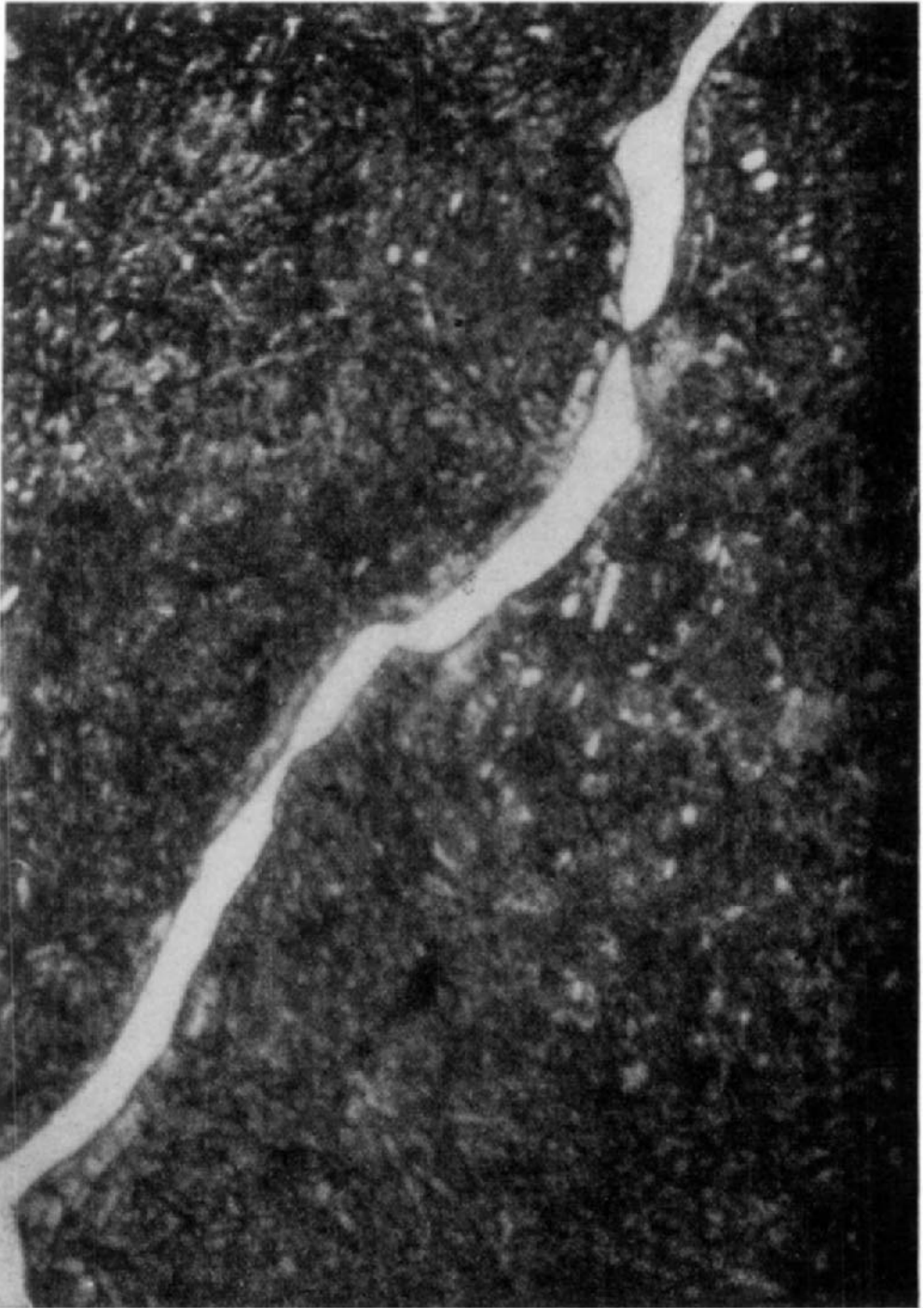
Quenched.

The Steel used in this Experiment had the following composition:

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C.	Mn.
1.41	.38%

FIGURE 25.



Magnification 5,000.

1.5 MM. APOCHROMAT.

TROOSTITE AND CEMENTITE.

Quenched and Tempered.

very indistinctly seen ; at the same time we are quite alive to the fact that they have not led us to any absolutely new discovery in the microstructure of Steel, and it is quite evident that there is an important field open for further investigations in this direction.

During the last few months we have been prosecuting enquiries in different directions with a view to obtaining apparatus which would enable us to attain much higher resolution than has been practicable with that at our disposal. While so far we have not been able to do this, several makers of apparatus and objectives in this Country are working at the problem, which we feel sure will soon be solved.

We have also been specially interested in the possibilities that might lie in the use of Ultra-violet Light for Photomicrography applied to Metal Sections. Who knows what new order of Phenomena may not be brought within our vision by the use of such apparatus. Researches are being made in this new field, and we all hope that such labours will be crowned with success.

In conclusion it is hoped that by presenting these Photomicrographs interest will be aroused in this special subject and that others will press forward investigations from which our general knowledge of the subject will benefit ; also that the makers of the necessary Apparatus, whether Microscopes, Lenses or Lighting Appliances, will come forward with new developments which will enable still further fields to be explored in the now Unknown.