VII. *A Research on Faraday's "Steel and Alloys."*

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PART I.

PART I.

§ 1.—INTRODUCTION.

It is surely not often that a paper such as this has been presented to the Royal Society dealing as it does with the research work carried out and described in its Proceedings by one of our Fellows more than a century ago. Still more rarely has it been possible, as in the present case, to be able to estimate the value of such research

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by a full examination of original specimens which have fortunately survived the long intervening period exactly as they left the hands of their maker.

I have endeavoured to describe the situation as it existed at that time and to submit this in Part I of the present paper, which deals with the historical side and general considerations.

In Part II is shown the actual research work, both scientific and technical, carried out in the examination of the FARADAY steel specimens at the Hadfield Research Laboratory, Sheffield, also a description of the methods adopted with regard to the large number of chemical determinations and metallographic examinations, mechanical, physical, heat treatment and other tests, and finally the general conclusions concerning the information derived from FARADAY'S "Steel and Alloys"—this is the term employed by FARADAY himself to designate the specimens and is therefore used by the author throughout the present paper—not only as regards the qualities of these alloys themselves, but also in furnishing valuable information useful to us to-day.

I venture to hope that this paper will be of special interest, coming as it does in the year devoted to the celebration of FARADAY'S many other scientific activities, besides those in the field of metallurgy and from all of which our own country and the world generally have so largely benefited.

During the period 1819 to 1824, when he was 28 to 33 years of age, MICHAEL FARADAY was engaged on an extensive and laborious research relating to alloys of steel with no less than sixteen different elements as well as four special compounds.

To understand FARADAY'S position at this time it should be mentioned that in March, 1813, he had been appointed Assistant in the Laboratory; in May, 1815, Assistant in the Laboratory and Mineralogical Section and Superintendent of the Apparatus. It was only later, February, 1825, that he became Director of the Laboratory under the superintendence of the Professor of Chemistry, and early in 1833 was made the first Fullerian Professor.

In his research work now described he had the co-operation of Mr. JAMES STODART, F.R.S., a maker of surgical instruments and a cutler, who was a man of eminence at that time. STODART (1760–1823) was considerably senior to FARADAY (1791–1867), and was elected a Fellow of the Royal Society in 1821, FARADAY himself not attaining this distinction until 1824. For these reasons the paper read by him before our Society on March 21st, 1822, and appearing in the 'Philosophical Transactions,' was entitled "On the Alloys of Steel: by J. STODART, Esq., F.R.S., and Mr. M. FARADAY, Chemical Assistant in the Royal Institution. Communicated by J. STODART, Esq., F.R.S."

It is, however, quite clear from this paper and an earlier one on "Experiments on the Alloys of Steel, made with a view to its improvement," presented to the Royal Institution by Mr. J. STODART, F.R.S. and Mr. FARADAY in April, 1820, that the actual work of preparing the alloys was done either by FARADAY himself at the Royal Institution or, in the case of the later and larger lots, the steel and alloys were made to his instructions at Sheffield.

Therefore, whatever FARADAY may have owed to STODART's experience as a practical maker of cutting instruments and to the facilities which STODART possessed for forging bars and tools in his factory, which was probably behind his shop at 401, Strand, London, the author has no hesitation in saying—after an exhaustive examination of all the circumstances and evidence—that the planning of the series of alloys, their preparation and the critical presentation of the results obtained must have been the work of FARADAY himself. Without any desire to underestimate STODART's attainments and assistance, it may safely be claimed that FARADAY is entitled to the credit of planning and carrying out the work as regards the alloying and the metallurgical aspect, with which alone the present author is concerned. For probably more than a century the seventy-nine specimens, each of which is fully described in the present research, have been kept in a small deal box which had been placed in one of the storerooms at the Royal Institution. The box is illustrated in fig. 1 (Plate 4) and the contents when taken out in fig. 2 (Plate 4). On the top of the box is a label with the word "FARADAY," believed to be hand-printed by him, and on one side a label with the words, "Steel and Alloys," definitely known to be in his own handwriting.

The melts from which these specimens were prepared, representing undoubtedly the most difficult part of the research, were carried out by FARADAY at the Royal Institution. The melted products remaining as "buttons" or small ingots were apparently allowed to solidify and cool down in the crucible. Their subsequent forging may have taken place in STODART's workshop. The author was, however, quite recently shown by Mr. W. J. GREEN, B.Sc., the Lecture Assistant of the Royal Institution, an inventory prepared in 1825 with regard to the contents of the storerooms in which appeared, amongst a long list of articles in the possession of the Institution, "a heavy hammer and anvil." It is therefore quite possible that in addition to the melting, the forging of the specimens as well may have taken place there. In that case the whole of the researches as regards the preparation of the specimens represented work carried out at the Royal Institution. In the same inventory, reference is made to the possession of a Daniell's pyrometer and other special apparatus of interest relating to and useful in a laboratory equipment devoted to the study of metallurgical problems.

These two important researches which FARADAY carried out, with the co-operation of STODART, as to the practical utilisation of the "Steel and Alloys," which is the term used by FARADAY to describe them, was undoubtedly the beginning of this important metallurgical research work on a preconceived and relatively comprehensive plan in this wide field.

Moreover, as entered in his Diary later on in his own handwriting, many further experiments, which may be termed the third portion of these researches, were carried out by FARADAY himself after STODART's death in 1823. These bore the dates November 3rd, 1823, February 10th, 1824, and June 28th, 1824.

At the time, FARADAY himself seems to have been somewhat disappointed with his results and certain of his biographers have dismissed his work on "Steel and Alloys" as of little importance, or have gone further and said that it ended in nothing. In this paper, the author hopes, however, to show—at the same time having due regard to the environment of those early days—how unfounded was this belief.

As regards FARADAY'S Diary, which is a model of its kind, this was commenced in the year 1820 after making his first experiments on "Steel and Alloys" in 1819. There are several entries in the first volume of his Diary, known as the "Green Book," to which Mr. THOMAS MARTIN, M.Sc., Secretary of the Royal Institution, has called my attention. Mr. MARTIN states that the three entries in this Diary for November, 1823, and February and June, 1824, are the only ones relating to steel between 1820 and the middle of 1832. After this date there is practically no reference by him of any kind to steel except a passing one in his correspondence with Dr. JOHN PERCY, F.R.S. Further, whilst his metallurgical papers to the Royal Institution and the Royal Society in 1820 and 1822 afford considerable information, the results are only given as general particulars and not in much detail.

By a happy combination of circumstances, related in this paper, the author has been able to subject most of the seventy-nine of FARADAY'S specimens found in the small wooden box to a very complete examination aided by the latest modern methods and resources. The results are presented in this paper, and from them it appears that, so far from FARADAY'S work being a failure, it actually constituted probably the first research ever made, and that a very remarkable one, on an extensive series of alloy steels. But for the proof afforded by the specimens themselves, and the present investigation of them and the knowledge so obtained, it could hardly be credited that such a successful research on the specimens produced by FARADAY could have been conducted in the state of knowledge, and with the comparatively poor resources available, 108 to 112 years ago.

Unfortunately, some of the interesting alloys mentioned in STODART and FARADAY'S papers, specially those containing very high percentages of platinum and rhodium, cannot be found.

Of the specimens tested, some appear to possess considerable merit as judged by the standards of FARADAY'S time and having in mind the purposes for which they were intended.

In considering this matter we must disregard for the moment all that we know concerning modern alloys, such as manganese steel, silicon steel, high-speed tool steels, heat and corrosion resisting steels, and all the other remarkable alloy steels of to-day. FARADAY was concerned with obtaining alloys which would make better knives, surgical and other cutting instruments than ordinary carbon steel and with discovering alloy steels that would, amongst other articles, produce mirrors which would be comparatively free from liability to rusting or tarnishing.

In view of the statements made in his two papers that he did, in fact, discover some steel alloys which were found to be of superior quality to those then made for cutting instruments and edge tools, it seems quite possible that these could have been used industrially or at least made the means of developing such steels after their further improvement.

As regards corrosion, judging from the small specimens examined by the author in this research, the results obtained did not differ materially from those of ordinary steel; in fact, this could not be expected now we know the composition of FARADAY'S steel determined by the author's examination.

§ 2.—CIRCUMSTANCES OF FARADAY'S RESEARCH.

In order to obtain a proper perspective of FARADAY'S work in this branch of steel metallurgy, it is necessary to refer to certain events which occurred during the closing years of the eighteenth century. About that time much interest had been aroused by the reputed remarkable properties of Wootz or Indian steel. Dr. HELENUS SCOTT, afterwards first Member of the Medical Board of the Bombay Presidency, sent specimens of this material to Sir JOSEPH BANKS, then President of the Royal Society, and who remained its President for no less than 42 years. At the instance of Sir JOSEPH BANKS, P.R.S., the nature and properties of Wootz or Indian steel were investigated by Dr. GEORGE PEARSON, F.R.S., who was assisted in this research by Mr. JAMES STODART, F.R.S. PEARSON'S results were announced in a paper presented to the Royal Society and published in the 'Philosophical Transactions,' 1795. In the course of that paper, PEARSON states: "That ingenious artist, Mr. STODART, forged a piece of Wootz at the desire of the President (Sir JOSEPH BANKS), for a penknife. . . . The edge was as fine and cut as well as the steel knife. Notwithstanding the difficulty of labour in forging, Mr. STODART from these trials was of opinion that Wootz is superior for many purposes to steel used in this country. We thought it would carry a finer, stronger and more durable edge and point. Hence it might be particularly valuable for lancets and other chirurgical instruments."

Evidently Wootz steel remained in high estimation for many years, for, as Mr. GEORGE H. GABB has pointed out to the author, one of STODART'S trade cards (probably about 1820), which may be seen in the British Museum, bears the inscription: "J. STODART, at 401, Strand, London, Surgeon's Instruments, Razors and other Cutlery made from Wootz, a steel from India, preferred by Mr. STODART to the best steel in Europe after years of comparative trial." It is equally evident, however, that the exact nature of Wootz steel continued to be somewhat of a mystery, for in 1819 FARADAY "analysed" by the imperfect methods of those days a specimen of this material cut from one of the cakes originally presented to STODART by Sir JOSEPH BANKS. In a paper* describing his procedure and results, FARADAY states that his object was to ascertain "whether any other substances were present in the Wootz than iron and carbon." He further says "Being engaged (1819) in the Laboratory of the Royal Institution with Mr. STODART, in a series of experiments on the alloys of steel, I was desirous, among other researches, to make an experiment, with a view to imitating Wootz." From this

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* 'Quart. J. Lit. Sci. Arts,' vol. 7, pp. 288–290 (1819).

it seems that the analysis of Wootz may have been undertaken with a view to obtaining data for its imitation, and certainly one of the earliest successes reported in the paper presented to the Royal Institution in 1820 is the preparation of a specimen which "had all the appreciable characters of the best Bombay Wootz."

Whether Wootz was the means of attracting FARADAY to the field of steel alloys, or whether he drew his inspiration from the interesting minute adopted by the Managers of the Royal Institution in 1812 to the effect that it was desirable that experiments should be undertaken with the alloys of metals, the fact remains that he was definitely interested in the preparation of this material by alloying, and he repeatedly compared his other steel alloys with Wootz, thus taking the latter as, in some measure, a standard of reference.

As to the manner in which FARADAY conducted his metallurgical work, including the preparation of his alloys, much information can be obtained from his famous and most valuable book, "Chemical Manipulation," a model of its kind, in which there are given clear and detailed descriptions of the construction and use of the "blast furnace," as FARADAY termed it, in which the steel was melted, and the crucibles he employed. This furnace is fully described in paragraph No. 184 of the book mentioned, and is shown in fig. 3. The laboratory in which the furnace was placed, situated in the basement of the Royal Institution, is shown in fig. 4 (Plate 5). The furnace consisted essentially of a blacklead or earthen crucible, in which broken coke was burnt with a draught provided by hand bellows. A small crucible containing the steel and alloying elements was embedded in the centre of the fire, a cover being placed over this crucible to protect the charge. With these simple resources, FARADAY states that he succeeded in melting pure iron "in twelve or fifteen minutes, the fire having been previously lighted"; and that this furnace "will effect the fusion of rhodium and even

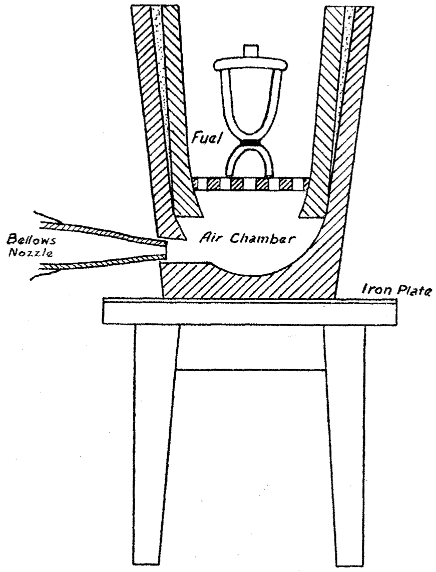

Fig. 3.—FARADAY'S Blast Furnace.

pieces of pure platinum have sunk together into one button in a crucible heated by it." In fact, the crucibles then available softened and fused before the furnace reached the maximum temperature which could otherwise have been attained. The difficult results obtained and described by FARADAY represent, therefore, quite remarkable performances. Moreover, the results of the analyses now presented by the author, showing, for example, the composition of the alloy steel specimen No. 31/D.4, which contained such a low percentage of carbon as 0·07 per cent., given in Table II, fully bear out and confirm that the foregoing statements by FARADAY were undoubtedly true.

Later on in the present paper reference is made to a number of experiments carried out by FARADAY in November, 1823, two months after STODART'S death, and continuing up to June, 1824. It is unfortunate that some of these specimens cannot be found, as, owing to the high percentages of the added elements platinum and rhodium, it might have been expected they would give alloy steels of particular interest. These steels were described in FARADAY'S own handwriting to be of the following nature: Specimen VII, steel containing 50 per cent. of platinum; VIII, steel containing 80 per cent. of platinum; IX, steel containing 50 per cent. of rhodium. There were also platinum and steel welded; steel twisted and forged to imitate damascened steel; pure iron fused; also iron with 3 per cent. rhodium and iron with 3 per cent. nickel.

None of the steel or iron alloys contained in the wooden box referred to has been found to contain such percentages as those mentioned. The highest percentage binary alloy steel specimen tested by the author and shown in Table II contained 2·79 per cent. copper (Specimen No. 29/D.2), another 1·50 per cent. Cu (No. 34/D.7), and one containing 2·36 per cent. Cr (No. 28/D.1).

The author specially calls attention to one of the results which FARADAY stated he had accomplished with the aid of his little "blast furnace," namely, the fusion in a clay crucible of pure iron with its high melting point of 1532° C., a really remarkable performance (1819–1824). That this was not an isolated case is proved by the author's analysis of the alloy steel specimen No. 31/D.4, just mentioned, which was found to contain the low percentage of 0·07 per cent. C and 2·25 per cent. Pt. This is further confirmed by the comparatively low Brinell hardness number of this particular specimen, as shown in Table No. IV.

How FARADAY accomplished such a feat in those early days of metallurgy it is not easy to understand, seeing the difficulty of obtaining the necessary high temperature to fuse pure iron with its high melting-point. The effect of carbon on the melting-point of this metal is shown by the following data, representing the latest determinations obtained regarding this important point. Pure iron is 1532° C.; steel containing 0·07 per cent. carbon, 1524° C.; 1·00 per cent. carbon, 1450° C.; 1·50 per cent. carbon, 1410° C.; 2·00 per cent. carbon, 1360° C.; 3·00 per cent. carbon, 1260° C.; and, finally, ordinary grade of pig iron, 1200° C.

As regards the supply of the special metals for the alloys, particularly the precious metals, platinum, rhodium, palladium, osmium and iridium, FARADAY freely acknowledged his indebtedness to that notable scientist, Dr. WILLIAM HYDE WOLLASTON, F.R.S., who furnished these not only for the small scale experiments in the Royal Institution Laboratory, but also, to use FARADAY'S words, "with a liberality which enabled us to transfer our operations from the laboratory of the chemist to the furnace of the maker of cast steel." The latter remark refers to the operations which were conducted in Sheffield on a comparatively large scale, as mentioned in the paper presented to the Royal Society by STODART and FARADAY in 1822. All the earlier and small scale experiments were conducted by FARADAY himself in the Royal Institution, and it was he who prepared and sent down the materials for the heavier melts made at Sheffield, resulting in ingots of 10 or 20 lb. weight. These ingots were made by Messrs. Sanderson, of Sheffield, under the supervision of FARADAY'S representative sent from London with the prepared and weighed materials. It seems that at about the same time an alloy of steel and silver, as devised by FARADAY, was stated as being used by Messrs. Green, Pickslay & Co., of Sheffield, for the manufacture of fenders and other articles; also, that the same firm was probably making razors of steel alloys containing rhodium, iridium and silver. Unfortunately, the evidence concerning these practical applications is very fragmentary and, notwithstanding a painstaking search, no trace of the steels obtained from these larger ingots made by the two firms above mentioned can be found, either in Sheffield or at the Royal Institution.

It was FARADAY'S enthusiasm which enabled so much to be done in the space of a few years with comparatively primitive resources, so that great credit is due to him for having inaugurated research on alloy steels. The specimens were undoubtedly made by FARADAY himself. Moreover, as examined by the aid of modern resources, they prove FARADAY to have been a metallurgical investigator of the highest ability, and the precursor or pioneer of alloy steels.

§ 3.—THE PRESENT RESEARCH.

In many respects the research now presented is unique. It has been conducted upon "Steel and Alloys," to use FARADAY'S own term, exactly as they left his hands about 110 years ago, though the specimens are small—79 of them weighing in all only 7 lb. 14 oz.—and only a fraction of each could be used by the author for analysis, physical and mechanical examination. Happily these means of testing are vastly superior to those then prevailing and available in FARADAY'S early days. As a consequence his results are now seen in a very different light from that in which they have hitherto been regarded.

It is many years since the author first read the two papers by STODART and FARADAY presented to the Royal Institution and the Royal Society, and he has long been familiar with FARADAY'S remarkable books "Chemical Manipulation" and "Experiments in Chemistry and Physics." On many occasions he has drawn attention to the fact that FARADAY was interested in and experimented on alloy steels, but he freely confesses that he had not appreciated the full importance and significance of this work until the opportunity arose of examining the specimens which FARADAY prepared.

In August of last year the author saw a few of these specimens of FARADAY's steel at the Science Museum, South Kensington, where they had been placed on exhibition, under the care of Sir HENRY LYONS, F.R.S., during the recent period of reconstruction of the Royal Institution building. In view of the fact that a general exhibition of FARADAY's instruments, apparatus and other material was to be held during the FARADAY Celebrations at the Albert Hall, under the management of a special Committee, with Colonel VIGNOLES as its Chairman, the author suggested that it would be interesting and appropriate to have these specimens of FARADAY's steel subjected to analysis and other examination. He further discussed this suggestion with Sir WILLIAM BRAGG, F.R.S., Fullerian Professor of Chemistry, Director of the Laboratory and Superintendent of the House, who now occupies the position so long held by FARADAY himself. It was recognised that FARADAY's researches on steel alloys and his own account thereof would acquire a new and greater interest if some of his actual specimens could be completely examined by the latest methods. It was therefore with much pleasure and satisfaction that on November 3rd, 1930, the author received an official letter from the Royal Institution stating that the Managers saw no objection to his proposal and granted the necessary permission for the examination and testing of these specimens.

This permission was granted not only regarding the few specimens then temporarily on view at the Science Museum, but also the whole of the contents of the wooden box shown in figs. 1 and 2 (Plate 4), of the existence of which before taking these over the author was entirely unaware.

By this decision it has been made possible to add materially to our knowledge of one branch of FARADAY's important work which the author claims represented this great scientist's first research of any considerable magnitude. Prior to 1819 when his metallurgical researches commenced, his other contributions to knowledge were represented by comparatively short communications to the Royal Society, the Royal Institution and other bodies. So far as the author is aware, there had not previously been any researches by FARADAY of an extensive nature such as the one now described on "Steel and Alloys," which was carried on for more than five years.

The problem which presented itself to the author for solution was no easy one; in fact, it was full of difficulties and pitfalls. At first it seemed almost hopeless to obtain much definite information from seventy-nine specimens of metal and of which only thirteen weighed 100 grams (3½ oz.) or over—the heaviest 140·10 grams (5 oz.)—while the remaining sixty-six averaged only 31 grams (1·10 oz.) each. Beyond a few special marks on some of the specimens—these are described in Table I, giving the particulars of the specimens arranged in their groups—there was practically nothing to indicate their actual nature, the probable composition, how made and treated, or other data. Information given in STODART and FARADAY's papers of 1820 and 1822 provided some useful clues, yet quantitative chemical examination of each specimen was entirely absent, nor could it very well have been otherwise in those days, seeing, too, that many of these "Steel and Alloys" of FARADAY contained such unusual constituents as platinum, rhodium, gold and silver, in themselves difficult to analyse. Their chemical determination, mechanical, electrical, magnetic and other testing, in most cases on small specimens, thus requiring much time and patience, proved very laborious—a labour of love to all concerned in the research, but a labour none the less.

To show the difficulties of the situation met with and which must have existed at that time and how imperfect were the methods prevailing with regard to the carrying out of chemical analysis, including the crude chemical notation employed when in 1819–1824 FARADAY was making his experiments on " Steel and Alloys," the author has thought it desirable to present one or two examples of these difficulties.

In confirmation with regard to the paucity of analytical information, it may be mentioned that in the whole of FARADAY'S two papers (1820 and 1822) on " Steel and Alloys," comprising some twenty-four pages of description, there is not given by him a single instance of even a partial analysis, much less a complete one. Even in his paper* on " Wootz or Indian Steel," read before the Royal Institution in 1819, he refers to the separation of " Silex and Alumine " with no other data, FARADAY'S exact wording being that the composition resulted in " 460 grains giving 0·3 of a grain of silex and 0·6 of a grain of alumine."

As there was no schedule or general description of any kind in the box nor has any record of these materials been found at the Royal Institution or elsewhere, the specimens had to be grouped and classified without any initial knowledge of their nature. Some of the specimens were imperfect, containing seams or other mechanical flaws, though on the whole they were sound enough for examination purposes, that is, considering their size and the difficulty of their manufacture in such small quantities. It should be realised that the ingots were quite small, varying from 1½ to 4½ oz. in weight. Quite a number of the alloys mentioned by FARADAY were not to be found among the seventy-nine existing specimens ; for example, it was unfortunate that some of the alloys containing high percentages of platinum or rhodium could not be traced. Proof that FARADAY actually made these is to be found in the fact that he gives measured values of their specific gravity, agreeing sufficiently well with the values calculated from their composition ; but not a single specimen of these special types has yet been found, though a most careful search has been made in the Royal Institution and in Sheffield.†

§ 4.—ANALYSES, TESTS AND OBSERVATIONS ON FARADAY'S SPECIMENS.

Turning now to the examination of the specimens, the first of those available was taken in hand on November 27th, 1930, and after some delays arising from the

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* ' Quart. J. Sci.,' vol. 7, p. 290 (1819).

† Since this paper was first presented nine small specimens of steel, also a razor used by FARADAY, have, by the kindness of Colonel Sir HENRY LYONS, F.R.S., the Director of the Science Museum, and with the consent of their owner, Mr. A. EVELYN BARNARD, been placed at the writer's disposal for full examination and a research on them is now in progress. This collection represents some of the alloy steel specimens of the higher percentages of platinum, rhodium, and palladium mentioned by FARADAY which have hitherto been thought to be missing.

difficulties of this unusual work, the analysis was completed on December 15th, 1930. The author was glad to find that the first specimen he picked out, No. 39/*b*/D.12-B, well-polished, bright and remarkably free from rust, contained 1·50 per cent. Pt. This gave great encouragement at the commencement of the work, as it entirely confirmed that FARADAY had definitely used the noble metals in making his experiments. Since the date mentioned, as shown in the main Table II, no fewer than 434 chemical determinations have been made on a total weight of 187 grams (6½ oz.), of the "Steel and Alloys" taken from the specimens in the form of drillings. The balance sheet as regards weight reads thus :—

	Grams.	lb.	oz.
(*a*) Total weight of drillings used in 434 chemical analyses	187·00	–	6½
(*b*) Wastage in preparing samples	390·00	–	13¾
(*c*) Remaining	3,002·00	6	9¾
Total	3,579·00	7	14

Actual determinations of fourteen different elements were made, yet the total weight of the steel drillings used for the analyses represents rather less than 6 per cent. of the original weight of the specimens.

The drillings used for each of the determinations were as follows :—

Sulphur	2·50 grams	Phosphorus ..	Either on the filtrate from the sulphur, or, when done separately, about 0·5 gm.
Silicon	1·00 ,,		
Chromium	1·00 ,,		
Copper	1·00 ,,		
Platinum, gold, rhodium, and other rare metals	On the silicon portion of 1 gram	Iron	0·27 gram.
		Silver	0·25 ,,
		Nickel	0·25 ,,
Carbon	0·50 gram	Manganese ..	0·10 ,,

(*Note.*—1 gram = 0·04 oz. approx. 28·35 grams = 1 oz.)

Apart from the chemical analyses, such tests as could be arranged from these small and difficult specimens have been made to determine the mechanical strength and hardness, also the electrical and magnetic qualities.

At the early stages of the investigation spectroscopic tests were usefully employed, though not in any thoroughly systematic way. From the advice given in this connection by Mr. F. TWYMAN, F.R.S., the author takes this opportunity of expressing his thanks.

The various information thus acquired is presented in full detail and discussed in Part II of this paper. The author hopes that, in view of the many difficulties encountered, the considerable amount of information presented will be regarded as a satisfactory accomplishment of this somewhat unusual and difficult type of research work.

Quite a number of the specimens were found to be of hard nature. This was naturally so, many being in the hardened or in some cases in the tempered condition; others were softer, being in the forged condition, evidently with no further treatment. As regards their quality, this representing ordinary high carbon steel, for the purpose for which they were no doubt intended, that is, fine tools, surgical and other instruments with cutting edges, it is quite possible that they may be excellent, though probably not more so than the best quality of modern crucible steel as now or even then made containing similar percentages of carbon. As regards the steels of the alloy type produced by Faraday, no evidence of any distinctly superior mechanical or other qualities has so far been detected.

In order, however, to test this fully and completely, a considerable series of experiments would be necessary, which it is not practicable to carry out with the small amount of material available and with specimens of such small size. It has, however, been possible to ascertain the nature and general properties of these original specimens, and, still more important to establish the credit due to Faraday for his remarkable pioneer work in this field of alloy steels, having in mind, too, the early date when he carried out the research. As the present investigation proceeded, the difficulty was not to obtain information, much of it of interesting character, but to keep it within reasonable compass. Facts of considerable interest were discovered, and useful suggestions were derived which later may well merit further investigation on larger specimens specially made for the purpose of more exhaustive researches. To this end the author hopes, if circumstances permit, to have the opportunity of making some of the higher percentage alloys of which Faraday speaks.

As to the exact number of samples of steel alloys made by Faraday, no information is available, but it is evident from the two papers by Stodart and Faraday that the total must have run into large numbers of experiments requiring heavy expenditure of time and money on these researches, and spread over about five years. Binary and ternary alloys were investigated, and altogether some sixteen elements and four other ferrous substances are mentioned by Faraday in connection with his researches. These, arranged alphabetically in groups, are as follows :—

Metallic Elements : Thirteen in number, seven being noble metals :—

1. Copper.
2. Chromium.
3. Gold.
4. Iridium.
5. Iron.
6. Nickel.
7. Osmium.
8. Palladium.
9. Platinum.
10. Rhodium.
11. Silver.
12. Tin.
13. Titanium.

Non-Metallic Elements : Three in number :—

14. Carbon.
15. Silicon.
16. Sulphur.

Other Ferrous Substances : Four in number :—

17. Wootz or Indian steel.
18. Carburet of iron.
19. Alumine alloy, so termed by FARADAY in 1820, in imitation of Wootz, also described as Damascene steel. (DAVY spoke of the added element as aluminum.)
20. Meteoric iron.

Of these alloy additions, the following have been actually determined by the author to be present in the various specimens of FARADAY'S steels examined by him :—Carbon, chromium, copper, gold, iron, nickel, platinum, rhodium, silicon, silver and sulphur. The elements osmium, iridium, palladium, titanium and tin, although stated to have been used, were not found in any of the specimens examined, but they only represented a small portion of the total number of ordinary steels, alloy steels and other ferrous substances prepared by FARADAY.

It will be noted that in this list of elements no reference is made to the metal manganese. This, however, is because in all FARADAY'S specimens there is an almost complete absence of this metal, of such importance to the world generally to-day for the production of industrial steels of all kinds.

As a matter of fact, in these researches by FARADAY, the metal manganese was never even mentioned by him, though he was well aware of its existence, judging by his paper* on the "Separation of Manganese from Iron," read before the Royal Institution in 1819, and still later when he conclusively proved that manganese was a non-magnetic metal, although this was some years later than the time when he was engaged on the research on "Steel and Alloys." In a note "On the General Magnetic Relations and Characters of the Metals : Additional Facts," dated February 7th, 1839, which appeared in FARADAY'S "Experimental Researches in Electricity," page 224, he said : "A piece of metallic manganese given to me by Mr. EVERETT was very slightly magnetic and polar at *common* temperatures. It was not more magnetic when cooled to the lowest degree." FARADAY, with his keen analytical mind, soon found that these samples contained small percentages of iron, so that riddle was soon solved.

In the various analyses made by the author, the maximum amount of manganese present in these specimens was 0·07 per cent., and the minimum only a trace. Thus all the steels examined showed little more than a trace of this element and evidently in no case had it been added.

Yet, singularly enough, the material termed spiegeleisen, or specular cast iron, a combination of manganese and high carbon, had been probably known as far back as the Middle Ages, as there are mines in existence where these spathic ores from which the spiegel was prepared have been won from Mother Earth for centuries past.

Sir HUMPHRY DAVY had also experimented with the metal manganese, or manganesum, as he termed it.

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* 'Quart. J. Lit. Sci. Arts.,' vol. 6.

On the other hand, JOSIAH MARSHALL HEATH, who later appeared on the scene with his manganese additions, had brought back Wootz ore from India in 1826, and was generally interested in steel, but did not in this respect, that is as regards his manganese additions, come forward until he brought out his invention with regard to using manganese some years later. HEATH was probably the first to discover and show practically the importance of the use of this metal manganese as applied to ferrous metallurgy.

One point may be mentioned which is rather an important one, that FARADAY had in mind the production of steel which would offer resistance to corrosion and rusting. In the 'Edinburgh Philosophical Journal,' vol. 7, April–October, 1822, conducted by Dr. BREWSTER and Professor JAMIESON, is given a replica of the STODART and FARADAY paper "On the Alloys of Steel," read before the Royal Society in 1822. On page 350 the following paragraph appears :—

> "From the 'Philosophical Transactions' for 1822.
>
> Having already laid before our readers, in vol. iii, page 308, an account of the early and very interesting experiments of Mr. STODART and Mr. FARADAY, on the Alloys of Steel with various metals, we avail ourselves of the earliest opportunity of printing the continuation of their valuable experiments.
>
> We attempted to make an abstract of this paper, but found the details too important to admit of any curtailment.
>
> Mr. STODART was so obliging as to favour us with specimens of several of these alloys for optical purposes, and though various plates of polished steel kept beside them for more than a year were all affected with rust, yet not one of the alloys have suffered the least change.—ED."

The above bears testimony to the interesting nature of the paper, and distinctly states that certain of the FARADAY specimens, the nature or composition of which is not designated, did not rust as compared with ordinary polished steels.

However, it can be stated very positively that none of the FARADAY steels examined by the author, amongst these seventy-nine specimens, can be said to have shown more than a slight improvement as regards resistance to corrosion. Therefore, either the specimens tested in Edinburgh were of different nature from those now examined, or the tests mentioned by Dr. BREWSTER and Professor JAMIESON cannot have been of a type sufficiently severe to discriminate between the specimens in regard to their resistance to corrosion. On the other hand, these specimens probably represented some of the missing steel alloys of high percentages and might therefore have possessed superior resistance to corrosion.

§ 5.—VALUE OF FARADAY'S METALLURGICAL WORK.

In the well-known biographies of FARADAY by Dr. BENCE JONES, F.R.S., in 1870, who was one of his personal friends, and by Professor SYLVANUS P. THOMPSON, F.R.S.

(1898), the impression appears to be conveyed that FARADAY'S research on steel and its alloys was a failure. In his obituary notice of FARADAY in the Royal Society Proceedings, BENCE JONES goes so far as to say: "The results of the paper on steel by STODART and FARADAY, to the Royal Society in 1822, were of no practical value, and this, one of his (FARADAY'S) first and most laborious investigations, is strikingly distinguished from all his other works by ending in nothing."

It may be that BENCE JONES, who in nearly every other subject valued FARADAY'S work most highly, did not weigh the full significance of the words "ending in nothing," and allowance must also be made for the fact that he was not a metallurgist. Moreover, he had not the advantage of being able to form an opinion, after a full examination of the various qualities of these specimens of FARADAY as is the case with the readers of this paper, who can better understand from the description of FARADAY'S metallurgical researches, here presented, how much valuable information they contain.

It must also be remembered that FARADAY himself appeared to underestimate the importance of his achievements when, in June, 1820, he wrote to his friend Professor GASPARD DE LA RIVE, at Geneva, "Pray pity us that, after two years' experiments, we have got no further; but I am sure, if you knew the labour of the experiments, you would applaud us for our perseverance at least." The present paper gives some idea of the great amount of labour involved, extending, as it did, over a period of five and a half years.

Again, much later in FARADAY'S life, on March 17th, 1863, he wrote the following letter which, in view of all the circumstances surrounding this subject, is of special interest. This was in reply to an enquiry from Dr. JOHN PERCY, F.R.S., who was at the time preparing one of the series of his books on metallurgy, in this case "Iron and Steel," which appeared in 1864. It may also be interesting to add that PERCY'S volume relating to the earlier portion of the series in question dealing with "Certain Physical Properties of Metals, General Considerations on Metallurgical Processes, Refractory Materials, Fuel, Copper, Zinc and Brass," published in 1861, and prepared by the "Government School of Mines," London, was dedicated "To MICHAEL FARADAY with the sincere respect and affectionate regard of THE AUTHOR."

"MY DEAR PERCY,

It is very pleasant to see your neat handwriting again.

I am quite tired in looking at my own unsteady, uncertain characters and sense.

I wish I could have the further pleasure of helping you, but I have forgotten all about the paper on alloys, and cannot at all call to mind where any of the specimens are.

I rather think they all went into Mr. STODART'S hands, and must be lost by this time, for I do not know how to trace them.

With kindest remembrances to Mrs. PERCY, from ever, my dear PERCY, yours affectionately,

M. FARADAY."

It must be remembered that FARADAY was then in his seventy-second year and his memory was seriously failing. Actually, the specimens had been carefully kept in the little wooden box shown in fig. 1 of this paper and placed in one of the storerooms of the Royal Institution.

It is quite possible that, but for this lapse of FARADAY'S memory, Dr. JOHN PERCY, F.R.S., would have obtained these specimens; nevertheless, great metallurgist though he was, he could not even in his day and generation have obtained from them in 1863 more than a fraction of the information which they have in these modern days been made to yield.

The article on FARADAY in the "Dictionary of National Biography" by Professor JOHN TYNDALL, D.C.L., LL.D., F.R.S., who was for so many years close to FARADAY in his thoughts, showed appreciation of the metallurgical researches in the following words: ". . . . . . jointly with Mr. STODART, FARADAY worked with success on the alloys of steel. A razor made of one of these alloys, and presented to the present writer by FARADAY himself, is still in his possession." Unfortunately, all attempts to find this razor have failed, but TYNDALL'S appreciation of FARADAY'S "success on the alloys of steel" remains.

As will be seen, although TYNDALL highly valued FARADAY'S metallurgical researches, his commendation rests perhaps not so much on the facts mentioned by him, but that these researches opened up an entirely new field of investigation.

Similarly, the late Professor Sir JAMES DEWAR, F.R.S., in an Address delivered at the FARADAY Centenary at the Royal Institution on June 26th, 1891, dealt with the chemical works of FARADAY in relation to modern science and spoke of FARADAY'S important work in connection with the investigation into properties or combinations of steel with other metals in the course of which he discovered certain important facts.

A careful perusal of STODART and FARADAY'S second paper, the one read before this Society, reveals much internal evidence that the work accomplished, as judged by the standards of previous knowledge and materials, constituted a considerable success and a marked advance at that time. It is an honour and privilege to have been given the opportunity of establishing these facts and proving by the resources of modern science that FARADAY is justly entitled to be regarded as the first to conduct deliberate researches on an extensive series of "Steel and Alloys."

In view of the state of metallurgical knowledge at the time these specimens were made, 1819–1824, the research taken as a whole may be considered as one of a remarkable character and, whatever their immediate practical value, it ought never again to be said that FARADAY'S investigations in this field "ended in nothing."

In the light of his own fifty years of experience in the field of ferrous metallurgy, largely concerned with alloy steels during the whole of this period, the author maintains that the steel alloys produced by FARADAY more than a century ago constituted another proof of his genius and foresight. They remain of great interest and importance, even to-day, and they represent a research which was certainly no failure, but rather a column built well and firmly as far as it went and then abandoned by its builder and others for reasons not now known, when it might eventually have been continued, as it was later by others, to a successful issue. Failure, as judged by the lack of continued practical application and development, lay not in FARADAY'S conception and research but in the fact that his work was not continued by others when he laid it aside. It must be remembered that outside certain comparatively small requirements, steel was then but little used, wrought iron was the material of the day. As showing this, it is doubtful whether an appreciable quantity of steel made more than a hundred years ago could be found to-day except in Museum and Collection specimens. Steel formerly made has disappeared, most of it, too, by corrosion.

Without doubt, no one before FARADAY—whether metallurgist, chemist, physicist or engineer—had ever experimented with so many elements in combination with iron. At that time, however, there was neither the same opportunity for continued research as there was later in the way of knowledge and resources, nor the same spur to investigation in the shape of insistent demand for steels of special quality, as regards mechanical strength, corrosion and other factors. In this sense, FARADAY'S research was long before its time, but that adds to, rather than detracts from, the credit due to FARADAY himself.

It is true that nothing of lasting practical value came immediately from FARADAY'S laborious research on "Steel and Alloys," but, in the light of all the facts, including the results of the present investigation, it cannot be denied that his work was indeed a brilliant anticipation of similar labours by later metallurgists, and that it passes triumphantly the acid-test of genuine and successful research—the search for and the discovery of fresh knowledge.

Part II.

The author, having described in Part I the historical and general aspects of Faraday's metallurgical researches, will now deal with the scientific and technical part of the present investigation. This is divided into the various sections shown in the Table of Contents.

§ 6.—Visual Examination and Classification of the Specimens.

Following the single specimen selected for a preliminary examination, 78 further specimens were received by the author, making a total of 79, forming the whole contents of the box shown in fig. 1. Fig. 2 (Plate 4) shows the specimens just as turned out from the box.

As a first step, the 79 specimens were classified by visual examination according to their individual form, and arranged in lettered groups, each specimen having its own group mark as shown in figs. 5 and 6 (Plates 6 and 7).

Under this classification to each specimen was allocated a group letter and number, these being stamped on the specimen in small characters or, where the material proved too hard, added by means of an electric engraving tool. In addition, each received a serial number from 1 to 79 described in the tables as the author's Research number, in order to distinguish them from any marks previously added by Faraday.

Each specimen was further carefully weighed and its dimensions taken.

It was hoped that this classification might provide some insight into Faraday's methods of working, if not of the actual nature and composition of individual specimens. Useful information was, in fact, obtained in this way.

Group " A " consists of three ingots weighing about $1\frac{1}{2}$, $3\frac{3}{4}$ and $4\frac{1}{2}$ ounces respectively. The metal had evidently been allowed to solidify in the crucible, from which it had afterwards been removed. These small ingots do not appear to have been mechanically worked in any way, nor do they show any signs of subsequent heating.

On the upper surface of Nos. 1/A.1 and 3/A.3 is a small excrescence which will be familiar to those having experience in the casting of metals, as due to the evolution of gases on solidification, and known in the steel industry as " rising."

Specimen No. 2/A.2 is more irregular in its form than the other two, that is, it is rather squat in character, and its exterior contour does not conform to the shape of a laboratory crucible, as do those of Nos. 1/A.1 and 3/A.3. It is to be inferred that in this case the crucible deformed during the process of melting, probably owing to a somewhat higher temperature being obtained, although the crucible was still able to retain its contents. Faraday, in his papers, refers to something of this kind occasionally occurring.

The pieces in group " B," weighing approximately 4 to 5 ounces each, are clearly ingots similar to those in group " A," but which have been hammered on four sides, probably preparatory to further forging. Adopting the language of the steel industry, they have therefore been described for convenience as "blooms." Specimen No. 10/B.7 is somewhat exceptional, a closer examination of which subsequently made indicates that it bears no signs of hammering, but is rather in the nature of specimen No. 2/A.2, that is, an ingot obtained from a melt in which the crucible has badly deformed owing to its semi-fusion.

Group "C" comprises definitely forged "bars" which, from their individual weights, ranging from 17 to 126 grams, might clearly have been derived from ingots such as those in group "A," passing, no doubt, through the stage represented by group "B."

While all these specimens are more or less rectangular in section, the smaller ones, represented by sub-groups C.2, 3 and 4, are rather more regular in shape. Again adopting the nomenclature of the steel industry, the specimens in group C.1 are conveniently described as "billets," and those in groups C.2, 3 and 4 as "forgings." A few of the specimens, such as Nos. 12/C.1–1, 13/C. 1–2, 14/C.1–3 and 15/C.1–4, are thinned out at one end, indicating that a portion of these specimens has been forged down to some smaller section, and cut off.

Specimen No. 20/C.1–9 is exceptional. It has a truly square section and is fractured at each end; in fact, on seeing it one cannot escape the idea that it may have been broken from a manufactured steel or iron bar. Clearly this does not fit in with FARADAY'S regular plan of dealing with the material he melted. On the other hand, he must certainly have had plain or ordinary carbon steel or iron for use as the raw material in the making of his alloys. It must be borne in mind that FARADAY speaks of his experiments as relating to "Steel and Alloys" as if the base material of his experiments in certain cases was steel, to which special elements were added, and in other cases wrought iron was the basis, though there are only a small number of these. The form represented by this specimen No. 20/C.1–9 would further seem to have been very convenient for packing into the crucibles. The possibility that this specimen represents the steel or iron base used in FARADAY'S experiments on alloy steels has, therefore, been specially considered later in studying the results of the chemical analyses and micro examinations.

Group "D" contains forged bars similar to those in group "C," though generally somewhat more regular in their rectangular section. The specimens are, however, distinguished by having one or more sides polished. Here we seem to have some relics of FARADAY'S efforts in the direction of obtaining alloys suitable for mirrors. Specimen No. 39/D.12 was, in fact, specially noticeable for the excellent mirror polish which it possessed, in no way diminished after this lapse of time.

The specimen originally selected from the contents of the box for a preliminary examination, prior to the investigation of the remaining 78, comes into this category "D." Like No. 39/D.12 it had, in fact, a high mirror polish on one side, and was also closely similar in its cross-sectional dimensions. For this reason it was allocated the author's Research number 39*b*, and group number D.12*b*.

Specimen No. 28/D.1, containing 1·59 per cent. C and 2·36 per cent. Cr, calls for particular comment, its two polished and adjoining faces being most beautifully coloured in a gradation of iridescent tints from blue through purple to a straw colour. The author will have occasion to refer to this specimen in more detail later.

In group " E," a new feature appears, that is, this group comprises specimens which have been prepared to certain uniform sizes. The whole of the 19 pieces in sub-groups E.1 and E.2 are all, within close limits, 3·10 × 1·10 × 0·55 cm. in dimensions, and have flat surfaces and squared-off ends. The purpose served by these specimens is not readily clear. They may have served as blanks for a cutting tool of some kind, for example, a razor or knife blade, with which to determine the practical cutting qualities of the various alloys. Specimen No. 70/G.1–1, to be referred to later, seems to be a knife blade probably intended for such a purpose. It would hardly, however, seem necessary for the production of such knife or razor blade to prepare the blanks in such a precise form as that represented by the specimens in sub-groups E.1 and 2. These specimens would rather seem to have been utilised as a standardised form of testpiece for closer comparison of the effect of a particular operation, say heat treatments of different kinds, on the various alloys. While undoubtedly they must have been prepared to size after forging, by mechanical preparation of the surface, say by filing or grinding, their " black " surface, as now presented, clearly indicates them to have undergone some form of heat treatment.

A further examination of these pieces showed that they had notches, from one to three in number, cut into them at one end, in much the same way as nowadays we mark test specimens to indicate differences either in composition or heat or other treatments. This particular marking was nevertheless useful as a further means of classification, as shown both by figs. 5 and 6 (Plates 6, 7). Its possible significance could naturally only be fully discussed after chemical and physical examination of the specimens, and reference to it will again be made later.

The presence of any other marks, having a possible significance, on any of the specimens was of course specially noted, and these will be found duly recorded in Table I. Of quite frequent occurrence was the mark " P " incorporated with the alchemist's symbol for iron, thus ♂. The presence of this mark on the specimens of sub-group E.1 was used by the author as a means of separating them from those of sub-group E.2 which bore no such mark. Specimen No. 25/C.3–1, it will be noted, also bears this mark, but with the substitution of the letter " R " for " P." Naturally these letters seemed to indicate the presence of platinum and rhodium which, as will be seen later on, was the case.

Continuing with group " E," the three specimens comprising sub-group E.3 are similar in form to those of E.1 and E.2, but they have irregular fractured ends. By squaring off these ends they could be brought to similar form, and it seems a fair inference that they are therefore unfinished pieces of the type represented by these earlier sub-groups.

The specimens in group E.4, while having the same characteristic of being prepared in a uniform size, and therefore probably representing some form of testpiece, have not the same dimensions as the other specimens of this group. They are cubical in shape, being 1·10 cm. square in section, with fractured ends, the length being approximately the same as the sectional dimensions.

The three specimens of group “F” labelled “Crude Steel from the Blast Furnace” single themselves out as of quite a different character from any others in the collection. Each is a broken fragment from a rectangular bar 3·10 × 1·20 cm. in section,* and their unwrought surface would seem to indicate that they are from material melted direct in Faraday's “Blast” Furnace and cast in a mould of this section. The labels on two of the pieces, Nos. 68/F.2 and 69/F.3, bear the additional word “annealed.” The handwriting on these specimens is that of Faraday. The analyses show them to be cast iron of highly sulphurous content.

The remaining nine specimens, each of which is individual and not classifiable into the previous groups, are all included in a further group “G.”

Specimen No. 70/G.1–1 is specially interesting, being definitely recognisable as a knife blank, the smaller end, which is taper in cross section, forming the blade, and the wider end constituting the tang which would be fitted into the handle. This specimen is one of those bearing the mark , and the addition of the word “STOD ART” in two separate parts is particularly interesting, indicating as it does that the knife was fabricated by Mr. James Stodart.

Specimen No. 71/G.1–2, being also of taper cross section, appears likely to have formed part of a blank intended for some form of cutting tool, and is therefore included with the previous specimen in a special group G.1. This specimen, was, in addition, highly polished over a portion of its surface.

Sub-group G.2 comprises four very small specimens, one of which, No. 73/G.2–2, is perforated with small holes in the manner of a wortle plate, such as used for wire drawing, and may conceivably have been intended for this purpose.

Specimen No. 76/G.3 is a complete and well-finished instrument the purpose of which, in the absence of any record, is difficult to decide. It is in two parts, the spear head and shaft being of steel or iron and fitting by a spring catch into a milled holder which is of brass. It might be described as a “harpoon” on a small scale.

Two small paper packets, Nos. 77/G.4–1 and 78/G.4–2, complete the collection. The writing on each of these is difficult to decipher, but is apparently “Platina no moment.” The packets each contain a small quantity of fine powder which is non-magnetic and weigh only 0·80 gram.

§ 7.—CONSIDERATIONS DETERMINING THE METHODS OF EXAMINATION EMPLOYED.

The importance, as relics, of this collection of specimens and the limited amount of material available imposed very careful consideration as to the manner in which their

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* The rectangular bar specimens were probably “blanks” from which to prepare experimental knives of the different steels. It is not clear, however, for what purpose the cubes were intended.

examination should be dealt with. On the other hand, in the almost complete absence of any direct information about any of the specimens, beyond such clues as had been obtained from the preceding classification, there was practically nothing to guide investigation. A specially difficult problem was therefore presented, and unless during the progress of chemical and physical examination certain points of similarity or connection between the different specimens appeared, nothing short of complete investigation of each individual specimen, both as regards its composition and physical condition seemed satisfactory.

Of first importance was to determine the chemical composition, without which little real knowledge could be achieved. Physical characteristics could obviously convey little without reference to analysis, while also it was very desirable to connect, if possible, the present specimens with such records as exist of FARADAY'S experiments in the alloying of iron with other elements.

As a preliminary step, one of the smallest specimens, D.12/B, HADFIELD Research No. 39/B, was selected for examination by the author with the following results.

§ 8.—METHODS OF INVESTIGATION.

(a) *Examination of Specimen No.* 39*B*/*D*.12*B*.

This specimen, 11 × 4½ mm. in section and 14 mm. long, with fractured ends, had evidently been broken from a longer bar. One of the 14 × 11 mm. faces still retained a mirror polish.

The very small amount of material available, the weight being only 6·066 grams, imposed even more care and consideration as to its economical use than the majority of the specimens in the collection. The procedure eventually adopted and the results obtained were as follows :—

Under the microscope at low power the polished face showed a high degree of finish in the centre, but scratches on the edges of the surface were so straight and parallel to each other as to render the conclusion fairly certain that the polish had been produced by machine and not by hand. The greater part of the polished surface was free from blemish, but corrosion had occurred in patches.

The specific gravity determination made on the whole piece gave a figure of 7·81, indicating that this particular specimen at any rate could not be one of those containing any specially high percentage of the heavy precious metals, such as platinum or rhodium.

Tests in the diamond Pyramid hardness tester gave the hardness in Brinell numbers as 750 on the polished face, and 735 on the back of the specimen. Conformably the piece was found to be unfileable, and to scratch glass. The hardness on Mohs' scale was 7½.

Metallographic examination followed, one of the surfaces of the piece being prepared for this purpose without cutting. This displayed the characteristic microstructure of a drastically quenched steel, an acicular troosto-martensitic structure with some austenite. The photomicrographs obtained are shown in figs. P.M.15 to P.M.19 (Plate 10).

For the purpose of chemical analysis the hard character of the specimen was perhaps fortunate. Although preventing drilling, it enabled a sample to be obtained more readily by pounding, and with a better yield of material.

Carbon was first determined on 0·5 gram by combustion with measurement of the volume of carbon dioxide produced. Duplicate determinations of iron on 0·27 to 0·28 gram each were next made by solution in dilute sulphuric acid, removal of metals precipitated by passing hydrogen sulphide and filtration, further reduction by gassing once more, boiling off the H_2S, cooling and titrating with a standard solution of potassium permanganate.

The washed H_2S precipitate, after ignition, was weighed, and on examination proved to consist chiefly of platinum.

Another portion of one gram was taken and silicon and platinum were quantitatively determined upon this.

Manganese was determined upon a further 0·1 gram, sulphur and phosphorus successively on the same weight of 2·5 grams. Tests were also made for chromium on 0·5 gram and for nickel on 0·25 gram, but the alloy proved to contain neither of these metals.

The total amount of sample used in the analysis was 5·41 grams, and, as will be seen, it had been found possible to determine not only the composition but the more important of the metallurgical features of the specimen on a weight of less than one-quarter of an ounce.

The examination of this specimen thus demonstrated the practicability of obtaining useful information upon a wide range of properties with a very limited supply of material and the mode of procedure adopted in this case proved generally applicable to the examination of the whole collection of FARADAY specimens.

The discovery of platinum in this first specimen examined, and that, besides its state of polish, its hardness bore evidence of FARADAY'S work in the heat treatment and manipulation of his alloys, was very encouraging towards the investigation of the remaining specimens, which therefore proceeded as follows.

(*b*) *Chemical Analysis.*

The chemical analysis of the FARADAY specimens has provided one of the most interesting series of problems ever undertaken by my chemical staff, for, in addition to the interest always attached to the search into the unknown, was the greater one afforded by the breaking of new ground in methods of analysis.

The need for constant care to ensure economy in the use of material was one of the main difficulties experienced. How far efforts in this direction were successful may be gauged by the following data:—

Specimens analysed .. 60. Determinations made .. **434**.
Weight of drillings used .. 187 grams.

Although the weights used in the analyses were necessarily cut down to the smallest possible amount, a high standard of accuracy has been maintained.

Amongst the problems which had to be solved, probably the most important was that of finding the most suitable method for determining the predominant metal present, namely, the iron. The ordinary direct method of solution of the sample in dilute sulphuric acid, followed by titration of the ferrous solution with standard potassium permanganate, gave low results with some of the platinum steels, leaving a deficit of three or four per cent. in the analysis. It will be readily understood that this gave rise to much anxiety until the solution of the problem was found. Eventually the method described below was worked out, thereby removing a very pronounced obstacle to the progress of the analytical work.

In a number of cases the chemical analysis was preceded by a metallographic investigation. Indications were thus afforded of the approximate carbon percentage, of abnormal proportions of sulphur, as in the case of the specimens of Group "F," and of the metallurgical nature of the material, giving valuable guidance in deciding the course to be pursued in the analysis. Some useful help in the same direction was also obtained from spectrographic examination.

In general, the samples for analysis were obtained by drilling. Such a method had the merit of preserving the external contour of the specimen, as well as any significance which might be attached thereto. Where this was not expedient, whether owing to the hardness of the material, or extreme limitation in the amount of material available, or other causes, the sample was prepared by pounding in a steel mortar, in some cases utilising portions of the material which had previously served for micrographic or other examination.

The general rule adopted was to determine the proportion of carbon and of iron, the two elements known to be present in every case. The sum of these, by the amount of its deficiency from 100 per cent., would indicate, subject to the considerations mentioned below, the amount of other elements to be looked for.

Iron.—The determination of iron afforded in its course much useful evidence as to other elements. The method adopted was to attack about 0·27 gram, weighed to the nearest 0·0001 gram, with dilute sulphuric acid, gently boiling. When visible action had ceased the liquor was inspected. Black insoluble floating matter indicated carbon. There was, however, in many cases an appreciable quantity of a heavy residue. At this stage the liquor was cooled and titrated with N/20 permanganate. The quantity consumed afforded a rough measure of the iron.

In some cases the end point was evanescent; this at once indicated that some other element was present and acting slowly. A slight excess of permanganate was added until on boiling a permanent precipitate of manganese peroxide was formed. The solution was next diluted so that it contained 8 c.c. of the sulphuric acid of sp. g. 1·8 in a total volume of 400 c.c. Hydrogen sulphide was then passed in to saturation, and the liquor heated and allowed to simmer for two minutes. It was then cooled, filtered and washed with 2 per cent. sulphuric acid containing H_2S.

The cold solution was again saturated with H_2S, boiled free from the gas and cooled and titrated with N/20 permanganate. The residue upon the filter was ignited and weighed, and afterwards examined for iron by extraction with hydrochloric acid and application of the sulphocyanide test. The amount thus determined, if any, was added to the main proportion determined in the second titration with permanganate, thus giving the percentage of total iron.

The iron determination was in every case made in duplicate, and, considering that 0·27 gram was taken, evidently the quantity of N/20 permanganate required would be nearly 100 c.c. A discrepancy of 0·1 or 0·2 c.c. would, therefore, represent an uncertainty of 0·1 or 0·2 per cent. of iron.

The figure for iron, therefore, is subject to a greater percentage error than that for any one of the other elements, but, nevertheless, its accuracy was obviously sufficient to preclude the missing of any significant amount of special alloying metal when the total of all elements found exceeded, say, 99·6 per cent. This was nearly always the case, and in view of the fact that direct tests were made to prove the absence of other elements than those actually found and determined, it is seen that the concordant testimony of the two lines of evidence is sufficiently conclusive to establish the substantial accuracy of the analyses.

The examination of the precipitate filtered off after adding hydrogen sulphide, including the portion originally insoluble in the sulphuric acid, disclosed in different samples the metals copper, gold, silver, platinum and rhodium. Tests were made for palladium, osmium and iridium, also tin, but none of these metals was found.

The weight of the precipitate just mentioned, after ignition, would roughly indicate the total quantity of the metals referred to, except in the case of copper which would be weighed as oxide. It may be seen, therefore, that with determinations of iron in duplicate, also of carbon on 0·5 gram, a total weight of very little more than one gram was made to yield a large amount of information.

Carbon.—The determination of this most important element was carried out on a weight of sample of 0·5 gram by the process of combustion in oxygen, the volume of carbon dioxide produced being measured.

Silicon.—The usual method for the estimation of silicon was only slightly complicated by the presence of noble metals. One gram was attacked with hydrochloric acid until action had ceased. On addition of a few drops of nitric acid the previously insoluble residue of gold, silver, platinum and rhodium, if any, was rapidly dissolved. The solution was then evaporated to dryness, heated on the hot plate, redissolved in hydrochloric acid and filtered, the residue washed, ignited and weighed in a platinum crucible. After weighing, a little hydrofluoric acid was added to the contents of the crucible, and the latter evaporated to dryness, and weighed again. The loss represented silica, from which silicon was calculated in the usual way. The residue and the filtrate were reserved for the determination of the precious metals.

Manganese.—As is well known, the proportion of manganese in steel is nowadays recognised as of considerable importance. This element manganese was, therefore, determined in representative members of each group. A weight of 0·1 gram was taken for this purpose, dissolved in dilute nitric acid, the manganese being oxidised with ammonium persulphate in the presence of silver nitrate, and the resulting permanganate titrated with sodium arsenite. In the majority of cases the permanganate colour produced by the oxidation was so slight as to make titration unnecessary for there was obviously only a trace present. The highest percentage found in any specimen was only 0·08 per cent.

Special Elements.—Naturally, the chief object and interest in the analysis lay in the identification and determination of the amount of the more special elements, where present, and the methods used for this purpose will next be outlined.

Chromium.—Only a brief account of this determination need be given as chromium steels are well known at the present day. One gram of the alloy was dissolved in sulphuric acid, oxidised with nitric acid, boiled, diluted, and the chromium oxidised with potassium permanganate in the usual way. The oxide of manganese was removed by filtration through asbestos, the solution being titrated with standard solutions of ferrous sulphate and potassium permanganate.

Nickel; with detection at the same time of Silver and Copper.—0·25 gram of sample was dissolved in hydrochloric acid, oxidised with nitric acid, diluted, tartaric acid added and the solution neutralised with ammonia, with the addition of the equivalent of 1 c.c. ammonia (0·88 sp. g.) in excess. The solution was cooled, and 2 c.c. of 2 per cent. potassium iodide added.

Where silver was present, this was evidenced by a turbidity caused by silver iodide. In any case the solution was then titrated with standard solutions of potassium cyanide and silver nitrate. The net consumption of potassium cyanide was equivalent to any silver, copper and nickel present.

About 0·1 gram sodium peroxide was added to the titrated solution to decompose cyanides, followed by addition of 5 c.c. of 1 per cent. alcoholic solution of dimethylglyoxime. The liquor was next brought to boiling and allowed to cool. The presence of nickel was indicated by the characteristic scarlet precipitate, even in the presence of silver iodide.

If more than a trace of nickel was thus revealed, a separate determination was carried out in which the copper and silver were first precipitated by hydrogen sulphide, the solution filtered, and the filtrate freed from H_2S and concentrated, by boiling. After oxidation with a few drops of nitric acid, tartaric acid was added, the solution was made ammoniacal, potassium iodide added, and titration made with potassium cyanide and silver nitrate.

The turbidity above mentioned, due to silver iodide, affords a very delicate indication. In the conditions stated, one drop of N/50 silver nitrate solution containing about 0·0001 gram of silver, produces a quite appreciable turbidity. This means that any silver over 0·04 per cent. can thus be detected.

Platinum, Rhodium, Gold, Silver.—The reserved filtrate and residue from the silicon estimation were used to determine the precious metals. The residue, if any, was easily removed from the crucible and was washed into the main filtrate, which was made slightly alkaline with ammonia and then acid with dilute sulphuric acid so as to contain 2 per cent. of free acid, as in the iron determination. Hydrogen sulphide was passed to saturation, the liquor filtered and the precipitate washed. The filtrate was again neutralised, made faintly acid and gassed once more. A further precipitate was produced here if rhodium was present. When hydrogen sulphide produced no further precipitate, the washed sulphides were ignited at about 800° C. and treated according to whether silver was or was not present, indicated as described under the determination of nickel.

In the absence of silver the ignited H_2S precipitate was extracted with hot hydrochloric acid to remove any copper oxide and traces of Fe_2O_3, and the cleaned metal filtered, ignited and weighed in a porcelain crucible.

The metals were then extracted with dilute aqua-regia, any platinum and gold dissolving. The insoluble metal, if any, was filtered off, ignited, reduced in hydrogen, weighed and identified as rhodium by fusion with potassium hydrogen sulphate solution in water, addition of hydrochloric acid causing the characteristic red coloration.

Where rhodium was present, the difference in weight after aqua-regia treatment was never more than 0·0005 gram, proving that platinum and gold were absent.

In the other cases complete solution was effected by the aqua-regia. This solution was evaporated with hydrochloric acid to remove nitric acid, and ammonium chloride added. Ammonium platinic chloride was precipitated if platinum was present, and in such cases the filtrate from this was tested for gold with stannous chloride. No purple colouration was ever found.

On the other hand, where the absence of platinum was shown by no precipitation with ammonium chloride, the purple colouration, known as purple of Cassius, was invariably produced on addition of stannous chloride. Thus the material soluble in aqua-regia was either platinum or gold, but not both. Any gold had previously given evidence of its presence by the brown colour of the ignited H_2S precipitate after the removal of base metals.

In the presence of silver the gently ignited metals were extracted with nitric acid, to remove the silver and copper oxide, washed with water and then extracted with hydrochloric acid. The two acid extractions were combined and evaporated to dryness, moistened with one drop of hydrochloric acid and diluted to 10 c.c., and the small precipitate of silver chloride filtered off, dissolved in ammonia and titrated with potassium cyanide and silver nitrate. The filtrate from the silver chloride was examined for copper as described below.

The remaining metals free from silver were then ignited and weighed, and extracted with dilute aqua-regia as above.

Tests for other Noble Metals.—The ignited hydrogen sulphide precipitate, as described above, was treated with aqua-regia. Any platinum was, of course, dissolved. As under some circumstances iridium, when present with a large excess of platinum, may be taken into solution by aqua-regia, it was necessary to take this into consideration. The precipitate produced by ammonium chloride, however, was always found to be of the pure yellow colour of ammonium platinic chloride. This would have been reddened had there been any iridium present.

The metal insoluble in aqua-regia, on fusion with potassium bisulphate, yielded in all cases a material completely soluble in water thus ruling out iridium here also.

It will have been seen that in cases where hydrogen sulphide gave a precipitate, this was always accounted for by metals other than iridium and osmium, which is always associated with iridium.

To test for palladium, the weighed metallic residue obtained by ignition of the purified H_2S precipitate was treated with aqua-regia and the solution freed from nitric acid by evaporation with hydrochloric acid. After dilution, potassium iodide was added. If palladium had been present a black flocculent precipitate would have been obtained, but no such precipitate was found.

Copper.—The analysis of the hydrogen sulphide precipitate in the course of the examination for precious metals on a one gram portion described above, afforded material for the determination of copper.

After removal of any silver from the acid soluble portion of the ignited precipitate, the solution containing copper, if present, was freed from traces of ferric oxide by ammonia and filtration, made acid with acetic acid, treated with potassium iodide and the liberated iodine titrated with sodium thiosulphate.

In two of the alloys, Nos. 29/D.2 and 34/D.7, large quantities of copper were indicated during the examination of the H_2S precipitate obtained in the determination of iron. The actual amounts were determined by dissolving 1 gram of the alloy in dilute sulphuric acid, precipitating with sodium thiosulphate in the boiling solution, filtering, igniting, removing traces of iron and proceeding as from the corresponding stage in the method just described.

Sulphur and Phosphorus.—In order to obtain evidence as to the kind of material used by FARADAY as the base of his alloys it was important to ascertain the proportions of sulphur and phosphorus in a few typical cases.

Other reasons led to the examination of specimen No. 68/F.2 for sulphur. The metallographic examination of this specimen showed the presence of sulphides in very large amounts, which suggested the reason for the considerable deficiency in the sum of the carbon and iron percentages, not in this case accounted for by the presence of other metals. Specimen No. 68/F.2 was, in fact, found to contain 1·76 per cent. of sulphur, and specimens Nos. 67/F.1 and 69/F.3 similar proportions.

Sulphur.—The analytical methods to be described were proved to be unaffected by the presence of the noble metals. The methods employed for sulphur differed according to the circumstances. In the more usual case where the sulphur content was normal in amount, a quantity of 2·5 grams was dissolved in aqua-regia, nitric acid removed by evaporation with hydrochloric acid, the silica rendered insoluble and filtered off and the filtrate evaporated until a skin of crystals was formed on the surface. This was just redissolved and 4 c.c. of hydrochloric acid added in excess. The solution was diluted to 70 c.c.; barium chloride was then added to precipitate the sulphur. The precipitate was allowed to settle overnight and was then filtered, washed, ignited and weighed as barium sulphate. The amount of barium sulphate derived from the reagents was determined by a control test and deducted.

In the case of specimens Nos. 67/F.1, 68/F.2 and 69/F.3 where the sulphur content is abnormal, the sulphur was evolved as hydrogen sulphide and absorbed in cadmium acetate solution. The sulphide in this solution was then titrated with standard iodine and thiosulphate solutions. 0·5 gram of the sample was mixed with 5 grams of a steel containing a known proportion of sulphur. This ensured the volume of hydrogen requisite to carry forward the H_2S, which was passed through two columns of cadmium acetate in series.

Phosphorus.—The filtrate from the barium sulphate in the gravimetric determination of sulphur was used. A slight excess of sulphuric acid was added to precipitate the excess of barium, the solution diluted to 250 c.c., filtered, and 200 c.c. of the clear solution collected. This was evaporated to about 70 c.c., ammonia added in slight excess, and the precipitate redissolved in nitric acid. The phosphorus was then precipitated with ammonium nitro-molybdate reagent. The yellow precipitate was filtered, washed and titrated with standard sodium hydroxide in excess, and sulphuric acid, using phenolphthalein as indicator.

In certain cases the purpose of the phosphorus determination was to reinforce the evidence from metallographic examination. As in these cases the material resembled wrought iron, a weight of 0·5 gram was used. This was dissolved in aqua-regia, evaporated and the residue heated to convert the phosphorus to orthophosphate, redissolved in hydrochloric acid, and the silica removed by filtration. Ammonia in excess was added to the filtrate, followed by nitric acid, the acidity adjusted, and precipitation made with ammonium nitro-molybdate solution. The remaining operations were as described above.

Special Features observed during Chemical Analysis.—In view of the unusual compositions found among these alloys, it may be of interest to describe some of the special features observed during the course of the chemical analysis.

The alloys were all readily soluble in aqua-regia, and those containing platinum, rhodium or gold, on addition of hydrochloric acid, were quickly attacked, leaving a small insoluble residue which was easily dissolved when nitric acid was added.

The effect of dilute sulphuric acid on the alloys containing platinum was very striking, which confirms FARADAY'S observations. On the addition of one volume of strong sulphuric acid to six volumes of water, considerable heat is evolved, as is well known When about 0·27 gram of any of the alloys containing platinum was added to 100 c.c. of this warm dilute sulphuric acid, the metal was instantly attacked, leaving after only a few seconds merely a small residue. This behaviour was peculiar to the platinum alloys; those containing rhodium or gold, none of which contained platinum, did not behave in this remarkable manner.

The examination of the alloys containing rhodium presented some interesting features. Thus, while the metal itself is insoluble in aqua-regia, those of the present alloys which contained rhodium, in fact all the alloys, as stated above, were easily soluble.

The removal of rhodium from a solution containing free sulphuric acid by means of hydrogen sulphide needed special treatment. The complete precipitation of the rhodium was only achieved by the addition of ammonia to the sulphuric acid solution saturated with H_2S, until a considerable quantity of ferrous sulphide was precipitated, this being just dissolved by the addition of dilute sulphuric acid. On again saturating with H_2S, the whole of the rhodium was precipitated.

The appearance of the noble metals derived from the ignited H_2S precipitate, after removal of co-precipitated iron, copper, etc., was characteristic. The platinum was grey, rhodium greyish-black, and gold earthy brown. On re-ignition the gold assumed its familiar lustre.

The analytical data thus obtained are completely recorded in Table I (pp. 251–253), the specimens here being placed in their serial order. While the principle was, as stated, to analyse where possible the majority of the specimens for carbon, iron and any special elements found present, the necessity or otherwise for estimations of other elements was decided from a study of the results as they were obtained during the course of the investigation. This will be made more clear in the comments upon the results generally.

Identification of the marks Ⓟ↗ and Ⓡ↗ with a platinum or rhodium content made it reasonably certain that the whole of the specimens of Group E.1 contained platinum. It was therefore felt that specimens Nos. 42/E.1–2, 44/E.1–4, 45/E.1–5 and 46/E.1–6 could, with advantage, and on this assumption, be allowed to remain in their original condition. The only possibility seemed to be that these specimens might contain some considerable percentage of platinum greater than that found in Nos. 41/E.1–1, 43/E.1–3 and 47/E.1–7, namely, about 1 per cent. This was safeguarded by the entirely non-destructive determination of specific gravity which was made on as many of the pieces in the collection as lent themselves to it, as shown in Table III (p. 256). The low figures obtained exclude, as will be seen, any such possibility, whether as regards the remaining specimens of Group E.1 or any others not chemically analysed.

As regards the specimens of Groups E.4 and G.2, in view of their very small size, it was thought that these could not profitably be investigated much further.

Although the absence of this special marking does not, conversely, preclude the presence of platinum or rhodium—nor of course other elements—since none of the seven analysed specimens from Group E.2 contains any special additions, it can reasonably be inferred that none of the remaining four, namely, Nos. 49/E.2–1, 51/E.2–3, 52/E.2–4 and 55/E.2–7, is alloyed to any appreciable extent, that is, even below a percentage which might sensibly affect the specific gravity.

TABLE I.—Chemical Analysis (per cent.).

1 Hadfield Research Number.	2 Group Mark.	3 Faraday's own Mark.	11 C.	12 Si.	13 S.	14 P.	15 Mn.	16 Cr.	17 Ni.	18 Cu.	19	20 Au.	21 Ag.	22 Pt.	23 Rh.	24	25 FE.
Group A.																	
1	A 1		0·84	0·22			0·04			0·02							98·78
2	A 2		0·69	0·02										0·80			98·25
3	A 3		0·92	0·28	0·021	0·030	0·05			0·02				0·73			97·90
Group B.																	
4	B 1		0·96	0·29			Trace					Nil	0·15 0·13				98·30
5	B 2		0·92	0·19										0·73			97·90
6	B 3		0·88	0·28	0·048	0·032	Trace					0·61	Nil				98·15
7	B 4		1·33	0·12			Trace						Nil	Trace	0·44 0·40		97·95
8	B 5		1·03	0·31									0·31	1·34	Nil		96·80
9	B 6		0·92	0·33			Trace						Nil	Nil	1·20 1·14		97·35
10	B 7		0·86	0·47			0·04	Nil	0·07 Ni + Cu				Nil	1·20			97·34
11	B 8		1·10	0·19								0·88	0·15	Nil			97·60
Group C.																	
12	C 1–1		1·24	0·14									0·46 0·35	Nil			97·90
13	C 1–2		0·94	0·19			Trace		0·75	0·04			Nil				98·05
14	C 1–3		0·94	0·33					0·07 Ni + Cu				Nil	0·74			97·60
15	C 1–4		0·94	0·30										0·69			98·30
16	C 1–5		0·77	0·24								Nil	Nil	Nil			99·10
17	C 1–6	1	0·61	0·05								Nil	Nil	2·50			96·70
18	C 1–7		0·84	0·33	0·027	0·031			Nil				Nil	0·68			97·90
19	C 1–8		1·15	0·24								0·60					97·90
20	C 1–9			0·09	0·025	0·032				0·15							
21	C 2–1	Ⓟ↗ 2	0·94	0·09										0·75			97·90
22	C 2–2		1·06	0·08					2·18	0·03		0·75					96·00
23	C 2–3		1·15	0·14								0·90	Trace	Nil			98·11
24	C 2–4		0·65	0·09			Trace		2·19	0·07			Nil				96·95
25	C 3–1	Ⓡ↗	0·97	0·19									Nil		1·60		97·50
26	C 3–2		0·24			0·107			0·13 Ni + Cu				Nil				99·80
27	C 4–1	2	0·90	0·33									0·26				98·40

NOTE.—The letters P and R in their circles on these various pages 251, 252 and 253, indicate respectively the presence of platinum and rhodium.

TABLE I. (continued).—Chemical Analysis (per cent.).

1 Hadfield Research Number.	2 Group Mark.	3 Faraday's own Mark.	11 C.	12 Si.	13 S.	14 P.	15 Mn.	16 Cr.	17 Ni.	18 Cu.	19	20 Au.	21 Ag.	22 Pt.	23 Rh.	24	25 Fe.
Group D.																	
28	D 1		1·59					2·36									96·10
29	D 2		1·05							2·79							96·30
30	D 3		0·93	0·24								Nil	Nil	Nil			99·10
31	D 4		0·07	0·07	0·022	0·108	Trace					Nil	Trace	2·25			97·70
32	D 5		1·09	0·07	0·029	0·051		0·54 0·52	Nil			Nil	Nil	Nil			98·25
33	D 6		0·88	0·33			Trace			Trace							98·90
34	D 7		1·30	0·14				Nil		1·50		Nil	Nil	Nil			97·10
35	D 8		1·44	0·26			Trace			0·08							98·00
36	D 9		1·04	0·15			Trace			Trace							98·60
37	D 10		0·96	0·24			0·04			Trace							98·50
38	D 11		0·94	0·10			Trace			0·12			Trace				98·60
39	D 12A		1·27														98·50
39B	D 12B		1·11	0·13	0·041	0·030	0·05	Nil	Nil	Trace				1·50			97·16
Group E.																	
41	E 1–1	Ⓟ↗ 3 nicks	1·12	0·14										0·90			97·50
43	E 1–3	Ⓟ↗ 3 nicks	1·20	0·16										1·05			97·80
46	E 1–6		0·94	0·14								Nil	Nil	1·15	Nil		97·60
47	E 1–7	Ⓟ↗ 2 nicks	1·30	0·13								Nil	Nil	1·10			97·30
48	E 1–8	Ⓟ↗ 1 nick															
50	E 2–2	3 nicks	1·52	0·09								Nil		Nil			98·16
53	E 2–5	2 nicks	1·50									Nil	Nil	Nil			98·40
54	E 2–6		1·47														98·30
56	E 2–8	2 nicks	1·48	0·07								Nil		Trace			98·27
57	E 2–9	1 nick	0·12		0·027	0·124	Trace										99·65
58	E 2–10	1 nick	0·07	0·14		0·128											99·2
59	E 2–11	1 nick	1·45	0·14					0·10 Ni + Cu			Nil	Nil	Nil			98·20
60	E 3–1		1·22	0·09			0·06						0·20				98·10
61	E 3–2		1·33	0·18										0·80			97·65
62	E 3–3		1·05	0·14										1·40			97·34

TABLE I (continued).—Chemical Analysis (per cent.).

1 Hadfield Research Number.	2 Group Mark.	3 Faraday's own Mark.	11 C.	12 Si.	13 S.	14 P.	15 Mn.	16 Cr.	17 Ni.	18 Cu.	19	20 Au.	21 Ag.	22 Pt.	23 Rh.	24	25 Fe.
								Group F.									
67	F 1	Crude Steel from the Blast Furnace	1·75	0·10	2·01	0·078	Trace		0·06 Ni + Cu								96·60
68	F 2				1·76												
69	F 3	Crude Steel from the Blast Furnace Annealed			1·73												
								Group G.									
70	G 1–1	Ⓟ↗ Stodart										Nil		Nil	Nil		99·0
71	G 1–2		0·95									1·0					98·0
76	G 3		0·93				0·07										98·7
								Stodart Specimens.									
Scalpel Blade			1·23				0·08										98·70
Old Razor with Ivory Handle			About 0·80				Not over 0·01										99·00

NOTE.—When analysing the samples dealt with in Tables I and II, in every case careful chemical examination was made to detect the presence of the noble metals, including palladium, osmium and iridium. None of these three elements was found to be present. This note applies also to tin.

With reference to specimens Nos. 40, 42, 44, 45, 49, 51, 52, 55, 63, 64, 65, 66, 72, 73, 74, 75, 76B, 77 and 78, these either formed members of definitely identified groups or were too small and unimportant to merit full examination. Though not chemically analysed they were subjected to spectroscopic examination.

TABLE II.—Classified Table of the Percentage Chemical Compositions of the Carbon Steels and Irons.

(Section 1.)

Hadfield Research Number.	Group Mark.	C.		Fe.
1	A 1	0·84		98·78
16	C 1–5	0·77		99·10
20	C 1–9		Cu. 0·15	
26	C 3–2	0·24		99·80
30	D 3	0·93		99·10
33	D 6	0·88		98·90
35	D 8	1·44		98·00
36	D 9	1·04		98·60
37	D 10	0·96		98·50
38	D 11	0·94		98·60
39	D 12A	1·27		98·50
50	E 2–2	1·52		98·16
53	E 2–5	1·50		98·40
54	E 2–6	1·47		98·30
56	E 2–8	1·48		98·27
57	E 2–9	0·12		99·65
58	E 2–10	0·07		99·20
59	E 2–11	1·45		98·20
70	G 1–1 Stodart	0·35		99·00
76	G 3	0·93		98·70
67	F 1	1·75	Sulphur 2·01	96·60
68	F 2		1·76	
69	F 3		1·73	

TABLE II (continued).—Classified Table of the Percentage Chemical Compositions of the Binary Steel Alloys.

(Section 2.)

Added Element.	Hadfield Research Number.	Group Mark.	C.		Fe.
Chromium				Cr	
	28	D 1	1·59	2·36	96·10
	32	D 5	1·09	0·54/0·52	98·25
Nickel				Ni	
	13	C 1–2	0·94	0·75	98·05
	24	C 2–4	0·65	2·19	96·95
Copper				Cu	
	29	D 2	1·05	2·79	96·30
	34	D 7	1·30	1·50	97·10
Gold				Au	
	6	B 3	0·88	0·61	98·15
	19	C 1–8	1·15	0·60	97·90
	23	C 2–3	1·15	0·90	98·11
	71	G 1–2	0·95	1·00	98·0
Silver				Ag	
	4	B 1	0·96	0·15/0·13	98·30
	12	C 1–1	1·24	0·46/0·35	97·90
	27	C 4	0·90	0·26	98·40
	60	E 3–1	1·22	0·20	98·10
Platinum				Pt	
	2	A 2	0·69	0·80	98·25
	3	A 3	0·92	0·73	97·90
	5	B 2	0·92	0·73	97·90
	10	B 7	0·86	1·20	97·34
	14	C 1–3	0·94	0·74	97·60
	15	C 1–4	0·94	0·69	98·30
	17	C 1–6	0·61	2·50	96·70
	18	C 1–7	0·84	0·68	97·90
	21	C 2–1	0·94	0·75	97·90
	31	D 4	0·07	2·25	97·70
	39B	D 12B	1·11	1·50	97·16
	41	E 1–1	1·12	0·90	97·50
	43	E 1–3	1·20	1·05	97·80
	46	E 1–6	0·94	1.15	97·60
	47	E 1–7	1·30	1·10	97·30
	61	E 3–2	1·33	0·80	97·65
	62	E 3–3	1·05	1·40	97·34
Rhodium				Rh	
	7	B 4	1·33	0·44/0·40	97·95
	9	B 6	0·92	1·20/1·14	97·35
	25	C 3–1	0·97	1·50/1·60	97·50

TABLE II (continued).—Classified Table of the Percentage Chemical Compositions of the Ternary Steel Alloys.

(Section 3.)

Added Element.	Hadfield Research Number.	Group Number.	C.			Fe.
Pt and Ag	8	B 5	1·03	Pt 1·34	Ag 0·31	96·80
Ag and Au	11	B 8	1·10	Au 0·88	Ag 0·15	97·60
Ni and Au	22	C 2–2	1·06	Au 0·75	Ni 2·18	96·00

TABLE III.—Specific Gravity.

Hadfield Research Number.	Group Number.	Specific Gravity.
39B	D 12B	7·81
42	E 1–2	7·82
44	E 1–4	7·79
45	E 1–5	7·80
46	E 1–6	7·84
48	E 1–8	7·84
49	E 2–1	7·78
51	E 2–3	7·79
53	E 2–4	7·70
54	E 2–6	7·80
55	E 2–7	7·80
62	E 3–3	7·86
63	E 4–1	7·81
64	E 4–2	7·81
65	E 4–3	7·81
66	E 4–4	7·75
70	G 1–1	7·83
72	G 2–1	7·79
73	G 2–2	7·53
74	G 2–3	7·79
75	G 2–4	7·97

For clearer study the specimens have been reclassified in Table II, the alloys being separated from the carbon steels and irons and grouped according to the alloying metal; the sections are (1) Carbon Steels and Irons; (2) Binary Steel Alloys; (3) Ternary Steel Alloys.

It is specially noteworthy that as regards their carbon content the specimens divide themselves into two categories. There are first those with low carbon, of which there are four, namely, Nos. 57/E.2–9, 58/E.2–10, 26/C.3–2, and 31/D.4 among those analysed. These range from 0·07 to 0·24 per cent. The remaining 50, although varying considerably in their carbon content, may all be classed as high; 20 range from 0·84 to 1·15 per cent., and 26 from 1·03 to 1·59 per cent. The "Crude Steel" specimens of Group "F" are excluded for the moment as being somewhat special.

In the case of two of the specimens, Nos. 17/C.1–6 and 24/C.2–4, showing by analysis 0·61 and 0·65 per cent. of carbon respectively, there is a definite explanation for these comparatively low values. That is, it subsequently proved, under micro-examination, that the surfaces of these pieces were decarbonised, the drillings including both low carbon material from the surface layers, and high carbon material from the interior. These steels must, therefore, be regarded as actually of higher carbon than the figures show.

The low value of the carbon content, 0·69 per cent. in the small ingot No. 2/A.2 is no doubt accounted for by excessive heating in the melting operation, as evidenced by its form and the resulting decarburising conditions. A similar remark, no doubt, applies to specimen No. 10/B.7, although the rather higher value of the carbon, 0·86 per cent., would seem to indicate that it has not been so much affected by the abnormal conditions during melting.

It is not surprising to find the majority of Faraday's steels and alloys high in carbon, since practically the only steel known in his day was of that character.

Of the low carbon materials Nos. 26/C.3–2, 57/E.2–9 and 58/E.2–10, their high phosphorus content and subsequent micro-examination clearly prove them to be wrought iron.

The carbon content of 0·24 per cent. of No. 26/C.3–2 is rather high for a wrought iron. Micro-examination later showed a typical wrought-iron structure at the centre of this specimen. The corners were, however, carburised, no doubt due to contact with some carbonaceous material during heating for forging. The sample for analysis was in this case taken from the whole cross section of the specimen, thus including some of the carburised material.

Specimen No. 31/D.4 is alloyed with 2·25 per cent. of platinum. To have obtained such a product with its carbon as low as 0·07 per cent. is no mean feat, which must excite the admiration of anyone who has melted steel and knows the difficulties, specially having regard to the simplicity of Faraday's equipment.

From the comparatively high phosphorus content of 0·108 per cent. in No. 31/D.4 there seems no doubt that wrought iron was used as the base.

Of the high carbon alloys, each of those analysed is comparatively low in phosphorus and, except in the case of specimen No. 32/D.5, remarkably uniform, namely between 0·030 and 0·032, No. 32/D.5 containing 0·051 per cent. The possibility that

No. 20/C.1–9 may represent some of the base material used in making the high carbon steels was therefore made more probable by this fact. Special care was in the circumstances taken with this specimen, the sample for analysis being taken by drilling along the central axis so as to preserve the exterior appearance.

Prior micro-examination of a transverse section, however, disclosed segregation of carbon. Clearly, therefore, any carbon figure obtained from the drillings could not be truly representative of the material, and no analysis of it for carbon was therefore made. This applies also to the iron, since the iron percentage is dependent upon variations in the carbon. Special elements as in other cases were, however, analysed for, but beyond 0·15 per cent. of copper nothing was found. This small amount of copper the author is inclined to regard as accidental and insufficient to justify the inclusion of specimen No. 20/C.1–9 among the alloy steels.

Thus, such investigation as has been possible tends to confirm that specimen No. 20/C.1–9 may actually represent some of the base material used by FARADAY in his steel and alloy melting experiments. Without extra carburisation of the melt, however, such material would be too deficient in carbon for producing some of the alloys with the highest carbon content as here found. It seems probable therefore, that FARADAY had at his disposal a selection of different grades of steel varying in their carbon content or "temper," of which this specimen No. 20/C.1–9 represents only one.

Specimen No. 28/D.1, to which attention has been previously called owing to its iridescent appearance, is found to contain, besides a specially high carbon content, 1·59 per cent., also 2·36 per cent. of chromium. There can be little doubt that this is the identical specimen referred to in the joint paper by STODART and FARADAY "On the Alloys of Steel," read in 1822, and in page 79 of FARADAY'S book, "Experimental Researches in Chemistry and Physics." He records concerning an alloy prepared by melting steel with 3 per cent. of pure chromium, that this after forging, polishing and being acted on by dilute sulphuric acid, gave a very fine damask. After re-polishing the damask was restored by heat without the use of acid. Now coloured by oxidation the damasked surface has a novel and beautiful appearance which was heightened by heating the metal so as to exhibit all the colours from pale straw to blue or from about 430° to 600° F. These remarks are of exceptional interest if only because they provide the only direct information concerning any of the specimens in the present research. The lower figure of 2·36 per cent. of chromium found in specimen No. 28/D.1, as compared with the 3·0 per cent. added by FARADAY, was to be expected for two reasons. The metallic chromium used by FARADAY could not have been of the purity obtainable to-day, and would not, therefore, yield 100 per cent. of its weight as a constituent of the alloy. In melting also, there would inevitably be some loss of the chromium due to oxidation, to which, as is well known by makers of alloy steels, this metal is particularly prone. Incidentally, it may be of interest to note that, although the carbon was higher, the chromium percentage did not differ much in this specimen from that in the type of steel used for armour-piercing projectiles about thirty years ago.

In view of the foregoing remarks by FARADAY, a closer visual examination was made of the surface of the specimen and this revealed, underlying the coloured surface, a delicate mosaic pattern which without doubt is the damask effect noted by FARADAY. Altogether the appearance of this specimen is indeed strikingly beautiful. No temper colours on steel which the author has seen have ever quite approached the richness of those produced by FARADAY, and one can understand his pleasure in them.

The composition of specimens of Group F, described as "Crude Steel from the Blast Furnace," is interesting but somewhat puzzling. The very high sulphur content of approximately 2 per cent. and specially high carbon would, however, seem to confirm that, unlike the remaining steels, they have been melted direct in FARADAY's blast furnace.

The red-shortness which was to be anticipated in such material was confirmed by the author, an attempt being made to forge a small piece from a corner of specimen No. 68/F.2 but without success, that is, the material easily burst.

Silver Steels.—It will be noted that the proportion of silver in such specimens as contain this element never exceeds 0·46 per cent. This fact finds its explanation in the very limited solubility of silver in steel, as well shown later in the microstructure of specimen No. 12/C.1–1. Here the silver is found as a distinct micro-constituent. It will thus be readily understood also why duplicate determinations of the silver content in this specimen showed different amounts.

This same fact did not escape the observant FARADAY, who, in his joint paper with STODART in the "Quarterly Journal of Science," published in 1820, mentioned that when a mixture of silver and steel was kept long in a molten state, a perfect alloy seemed to be formed: but on solidification, globules of silver appeared on the surface of the button. When a forged bar of this metal was acted on by dilute sulphuric acid, the silver was left in threads through the mass, "so that the whole has the appearance of a bundle of fibres of silver and steel as if they had been united by welding."

(*c*) *Determination of Hardness.*

For this purpose the Diamond Pyramid hardness test was employed in preference to the Brinell. The smallness of its impressions was of value in causing less mutilation of the specimens, and for the higher hardnesses its indications are more reliable.

The preparation of a smooth surface on an unused portion of the specimen was usually unnecessary, advantage being taken of any cut surface, or the region close to a drill hole where the surface had previously been removed.

These hardness determinations are recorded in Table IV, the figures obtained having been converted to equivalent Brinell numbers by means of a calibration of the apparatus made for that purpose.

TABLE IV.—Hardness Expressed on the Brinell Scale with the Estimated Tensile Strength.

These hardnesses determined by the Diamond Pyramid hardness test have been converted to equivalent Brinell figures.

Actual tensile specimens from material of over 550 Brinell hardness do not display their full yield strength or tenacity owing to their tendency to break prematurely, and the tensile data in such cases are therefore shown in italics.

Hadfield Research Number.	Group Number.	Brinell Hardness.	Tensile Strength.	
			Yield Point.	Maximum Stress.
			Tons per square inch.	
		Group A.		
1	A 1	262	47	58
2	A 2	143 195	20 31	35 45
3	A 3	260	47	58
		Group B.		
4	B 1	240	41	54
5	B 2	210	34	48
6	B 3	234	40	53
7	B 4	265	47	58
8	B 5	295	54	63
9	B 6	268	48	59
10	B 7	270	49	59
11	B 8	300	55	64
		Group C.		
12	C 1–1	230	39	52
13	C 1–2	275	50	60
14	C 1–3	230	39	52
15	C 1–4	240	41	54
16	C 1–5	235	40	53
17	C 1–6	730 244	42	55
18	C 1–7	314	58	67
19	C 1–8	260	47	58
20	C 1–9	180	27	42
21	C 2–1	250	44	56
22	C 2–2	300	55	64
23	C 2–3	278	51	60
24	C 2–4	276 176 690	50 41 26 *157*	60 54 41 *174*
25	C 3–1	260 280	47 51	58 61
26	C 3–2	140	19	34
27	C 4	274	50	60

Table IV (continued).

Hadfield Research Number.	Group Number.	Brinell Hardness.			Tensile Strength.					
					Yield Point.			Maximum Stress.		
					Tons per square inch.					
Group D.										
28	D 1	330	630		62	*140*		70	*153*	
29	D 2	645	395		145	78		158	85	
30	D 3	272			49			59		
31	D 4	175	180		26	27		41	42	
32	D 5	260			47			58		
33	D 6	230			39			52		
34	D 7	322			60			68		
35	D 8	280			51			61		
36	D 9	295			54			63		
37	D 10	286			52			62		
38	D 11	288			53			62		
39	D 12A	560			*120*			*132*		
39B	D 12B	750	735							
40	D 13									
Group E.										
41	E 1–1	735	688		—	*157*		—	*174*	
42	E 1–2	740								
43	E 1–3	714	664		—	*150*		—	*165*	
44	E 1–4	745								
45	E 1–5	450			92			100		
46	E 1–6	250			44			56		
47	E 1–7	228			39			52		
48	E 1–8	240			41			54		
49	E 2–1	720								
50	E 2–2	675	414		*153*		82	*169*	89	
51	E 2–3	600			*132*			*145*		
52	E 2–4	740								
53	E 2–5	510	460	520	107	95	110	118	103	121
54	E 2–6	200			32			46		
55	E 2–7	245			43			55		
56	E 2–8	236	230		40		39	53	52	
57	E 2–9	128			17			31		
58	E 2–10	185			28			43		
59	E 2–11	196	198		31		31	45	46	
60	E 3–1	285	282		52		51	62	61	
61	E 3–2	322	288		60		53	68	62	
62	E 3–3	320			60			68		
63	E 4–1	120			16			30		
64	E 4–2	117			16			30		
65	E 4–3	140			20			35		
66	E 4–4	140			20			35		

TABLE IV (continued).

Hadfield Research Number.	Group Number.	Brinell Hardness.	Tensile Strength.	
			Yield Point.	Maximum Stress.
			Tons per square inch.	
Group F.				
67	F 1	328	62	70
68	F 2	230	39	52
69	F 3	195	31	45
Group G.				
70	G 1–1			
71	G 1–2	670	*152*	*167*
72	G 2–1	310	57	66
73	G 2–2	435	88	94
74	G 2–3	355	68	75
75	G 2–4	280	51	61
76	G 3	210	35	48
76B	G 3B			
77	G 4–1			
78	G 4–2			

It will be seen that on 14 of the 75 specimens tested, a figure of 600 Brinell or over, indicating glass-scratching hardness, is obtained. Quenching thus played a prominent part in FARADAY'S experimental work. Eight of these hardened specimens are found in Groups E.1 and 2, thus pointing to these specimens of specially prepared form being intended for heat treatment experiments. The hardness figures obtained on these groups in fact seem to provide some further clue in this connection, although still not a complete one. Thus it will be seen that it is the first four specimens only of each group, E.1 and E.2, which are of over 600 hardness. These are the ones having three nicks cut in them. Nos. 45/E.1–5 and 53/E.2–5, each with two nicks, are of an intermediate hardness, 450 and 460/520 respectively. The remainder, Nos. 46/E.1–6, 47/E.1–7, 48/E.1–8, and 54/E.2–6, 55/E.2–7, 56/E.2–8, 57/E.2–9, 58/E.2–10, 59/E.2–11, are all of comparatively low hardness not exceeding 250. Here, however, the connection with the marking ceases, because some of these have two nicks, like Nos. 45/E.1–5 and 53/E.2–5, and some only one.

As regards the hardness figures below about 600, lack of information as to the heat treatment, if any, given to the various specimens, prevents these figures being as useful as they might otherwise have been. It will be seen later from the micro-examination that many of the specimens are in a condition just as forged without further heat treatment. Mainly in connection with this micro-examination definite heat treatments, accompanied by hardness measurements, have, however, been carried out by the author, specially in view of the "novelty" of some of the alloys.

It will be noticed, however, that the "iridescent" specimen, No. 28/D.1, of which an indication of its heat treatment is actually given by FARADAY, varies in its hardness from end to end between 630 and 330, no doubt explained by differences of temperature in the tempering operation. No. 29/D.2 varies in a similar way between 645 and 395.

Specimens Nos. 17/C.1–6 and 24/C.2–4 are two others which vary in their hardness at different positions. This is explained by decarbonisation of the surface, probably resulting from the heating operations these pieces had experienced either in forging or hardening. In each of these cases the lower hardness figure was obtained on the surface, and the higher at the centre of a cut section.

It will be noted that of the high sulphur specimens in Group F, the two Nos. 68/F.2 and 69/F.3 labelled by FARADAY as "annealed," are definitely softer than No. 67/F.1 not so described, the figures being 230 and 195 as against 328.

The knife blank specimen No. 70/G.1–1 has evidently been hardened and tempered ready for final grinding and finishing, the blade portion having a hardness of 470 near the edge and 340/370 at the back. At the remote end of the tang the hardness is only 190.

In Table IV, accompanying the hardness figures, is an estimate of the tensile strength of the specimens as deduced from their hardness. Such an estimate, while fairly closely correct for hardnesses up to 550 Brinell, must necessarily be accepted as approximate for hardnesses above that figure for the reason mentioned at the head of the table ; that is, while the figures given for the very hard specimens probably represent the true approximate yield strength and tenacity of the material, in an actual tensile test such high figures would not be reached owing to the tendency for the test specimen to break prematurely.

(*d*) *Metallographic Examination.*

The examination of polished and etched specimens under the microscope, and the interpretation of the structures thus revealed, is one of the methods of investigation developed since FARADAY's day. The application of this method to his specimens was, therefore, of peculiar interest, but, added to this, was the important consideration that it afforded an opportunity for the first time, so far as the author is aware, of determining the effect on the microstructure of additions of the noble metals platinum and rhodium to steel. It was also desirable to test the response of certain of the special alloys to heat treatment, so far as the available specimens permitted.

One of the objects of the metallographic examination was naturally to obtain a permanent record of the microstructure of typical specimens, and this was effected with the aid of an installation of a new type and design, known as the Hadfield-Beck metallurgical microscope.

In the special circumstances of the present research, owing to the limited weight of many of the specimens, the interdependence of the data provided respectively by the chemical and the metallographic methods of examination, as now used, is well exemplified.

Reference has also been made, in describing the methods of chemical analysis employed, to the utilisation of information derived from a preliminary examination under the microscope.

Particular attention has also been drawn to the very unusual amounts of sulphur in the specimens of group F, which were first revealed as large inclusions of sulphide under the microscope, leading to their determination by chemical analysis; see Photomicro, fig. PM. 8 (Plate 8), in which typical inclusions of iron sulphide are shown.

The preparation of the specimens did not occasion any special difficulties. It might have been expected that some difficulty would be experienced in etching the microsections of the steels containing the precious metals, but this was not the case, and all of them, irrespective of their composition, were etched satisfactorily in the usual reagent, namely, one volume of nitric acid in 100 volumes of ethyl alcohol.

Boiling alkaline sodium picrate was effective in revealing the location of free carbides in all the specimens in which these were present, as judged from other tests. The free carbide was darkened in a similar manner to the cementite in carbon steels.

A solution of soldium sulphide in water proved effective in revealing the mode of occurrence of silver in the specimens containing that metal.

Particulars of the microstructure of the specimens examined are given in Table V, A and B. Section A refers to the specimens in the condition as received by the author, and Section B records particulars of selected specimens after forging or heat treatment in the author's laboratory. Photomicrographs illustrating the various structures met with are given in figs. PM. 1 to 30 (Plates 8–12).

TABLE V.—Metallographic Examination.

(*a*) Specimens in the condition as received by the author.

Hadfield Research Number.	Group Number.	Analysis.			Photo-micrograph Number.	Description of Microstructure.
		C. per cent.	per cent.	Fe. per cent.		
						(1) Carbon Steels and Irons.
						WROUGHT IRONS.
57	E 2–9	0·12		99·65	P.M. 1	Ferrite grains and slag. Typical of wrought iron.
58	E 2–10	0·07		99·20		Ferrite grains and slag. Typical of wrought iron.
26	C 3–2	0·24		99·80	P.M. 2	Ferrite grains and slag. Typical of wrought iron, but with some irregular carburisation at the surface, chiefly at the corners.
						CARBON STEELS.
20	C 1–9	Variable. 0·25 to 0·90			P.M. 3 P.M. 4	Variable. Grains of ferrite and lamellar pearlite. Small areas of pearlite only, in the centre.
33	D 6	0·88		98·90	P.M. 5	Granular, with traces of lamellar pearlite. A few grains of ferrite.
50	E 2–2	1·52		98·16		Groundmass shows a graduation of tempering structures from troosto-martensite to sorbite. Small globules of free carbide. Grain boundaries outlined by cementite.
56	E 2–8	1·48		98·27	P.M. 6	Groundmass of granular with traces of lamellar pearlite. Numerous spheroids and nodules of free cementite in groundmass and grain boundaries.
						HIGH SULPHUR STEEL.
68	F 2	1·75	S. 1·76	96·60	P.M. 7 P.M. 8	Coarsely spheroidised carbide in a groundmass of ferrite. Numerous and large inclusions of iron sulphide.

Table V (continued).

(*a*) Specimens in the condition as received by the author (continued).

Hadfield Research Number.	Group Number.	Analysis.			Photo-micrograph Number.	Description of Microstructure.
		C. per cent.	per cent.	Fe. per cent.		
						(2) Binary Steel Alloys.
						Chromium Steels.
32	D 5	1·09	Cr. 0·52	98·25		Sorbitic pearlite and spheroidal carbide. Primary grain boundaries indicated by non-metallic inclusions.
28	D 1	1·59	2·36	96·10		Non-acicular troosto-martensitic groundmass. Primary grain boundaries marked by small globules of free carbide, also a smaller grain structure outlined by free carbide.
						Nickel Steel.
24	C 2–4	0·65	Ni. 2·19	96·95	P.M. 9	Sorbitic pearlite core with severely decarburised and oxidised surface.
						Copper Steel.
29	D 2	1·05	Cu. 2·79	96·30	P.M. 10	Lamellar pearlite.
						Gold Steels.
19	C 1–8	1·15	Au. 0·60	97·90		Finely laminated pearlite. Primary grain structure shown by slight segregation.
6	B 3	0·88	0·61	98·15	P.M. 11	Lamellar pearlite with traces of ferrite.
23	C 2–3	1·15	0·90	98·11		Finely laminated and granular pearlite. A little free carbide in the grain junctions.

TABLE V (continued).

(*a*) Specimens in the condition as received by the author (continued).

Hadfield Research Number.	Group Number.	Analysis.			Photo-micrograph Number.	Description of Microstructure.
		C. per cent.	per cent.	Fe. per cent.		
						(2) Binary Steel Alloys (continued).
						SILVER STEELS.
4	B 1	0·96	Ag. 0·15/0·13	98·30		Finely laminated pearlite. Traces of free ferrite. A number of small inclusions, identified as metallic silver, associated with the non-metallic inclusions.
60	E 3–1	1·22	0·20	98·10		Finely laminated pearlite with free carbide in the grain boundaries, and as needles within the grains. A few large particles of carbide, the remnants of a eutectic. Some small inclusions of metallic silver.
12	C 1–1	1·24	0·46/0·35	97·90	P.M. 12	Groundmass of ferrite and spheroidal carbide. Some larger particles of carbide located on pre-existing large grain boundaries. Numerous groups of small inclusions of metallic silver.
						PLATINUM STEELS.
3	A 3	0·92	Pt. 0·73	97·90		Finely lamellar pearlite. Occasional unsoundness along grain boundaries.
14	C 1–3	0·94	0·74	97·60	P.M. 13	Granular pearlite. Primary grain boundaries faintly traceable, outlined by nodules of free carbide.
2	A 2	0·69	0·80	98·25	P.M. 14	Grains of ferrite, and of lamellar to spheroidal pearlite. Numerous cavities.
41	E 1–1	1·12	0·90	97·50		Non-acicular troosto-martensite. Shows bands of more troostitic material. Numerous small globules of free carbide. Some large particles of free carbide, the remnants of a eutectic.
43	E 1–3	1·20	1·05	97·80		Very similar to E. 1–1.
10	B 7	0·86	1·20	97·34		Finely laminated pearlite, traces of ferrite. Unsoundness along some of the grain boundaries.
39B	D 12B	1·11	1·50	97·16	P.M. 15–19	Striated structure. Dark troosto-martensitic groundmass, light striae of fine acicular martensite. Traces of austenite. Small spheroids of free carbide. The structure is that of a drastically quenched steel.
31	D 4	0·07	2·25	97·70	P.M. 20	Ferrite grains, showing strain lines due to cold work.
17	C 1–6	0·61	2·50	96·70	P.M. 21	Varies from ferrite at the surface, to granular and traces of lamellar pearlite, with a little ferrite, in the centre. Unsound and shows cracks. Severely decarburised at the surface.

TABLE V (continued).

(*a*) Specimens in the condition as received by the author (continued).

Hadfield Research Number.	Group Number.	Analysis.			Photo-micrograph Number.	Description of Microstructure.
		C. per cent.	per cent.	Fe. per cent.		
(2) Binary Steel Alloys (continued).						
						RHODIUM STEELS.
7	B 4	1·33	Rh. 0·44/0·40	97·95		Finely laminated pearlite, rather thick grain boundaries of carbide. Local traces of eutectic structure and numerous non-metallic inclusions indicate primary grain boundaries.
9	B 6	0·92	1·20/1·14	97·35		Finely laminated pearlite. A little free ferrite, together with non-metallic inclusions and some unsoundness, all indicate the primary grain boundaries.
25	C 3–1	0·97	1·50/1·60	97·50	P.M. 22	Finely laminated pearlite, on which primary grain structure is indicated by slight segregation. Non-metallic inclusions chiefly in boundaries of the primary grains.
(3) Ternary Steel Alloys.						
						PLATINUM-SILVER STEEL.
8	B 5	1·03	Pt. Ag. 1·34 0·31	96·80		Finely laminated pearlite. Small nodules of free carbide, metallic silver and non-metallic inclusions, all lying in primary grain boundaries.
						GOLD-SILVER STEEL.
11	B 8	1·10	Au. Ag. 0·88 0·15	97·60		Grains of finely laminated pearlite. Numerous small inclusions of metallic silver.
						GOLD-NICKEL STEEL.
22	C 2–2	1·06	Au. Ni. 0·75 2·18	96·00	P.M. 23	Finely laminated and granular pearlite. Slight segregation indicates primary grain structure. Non-metallic inclusions of usual appearance.

TABLE V (continued).

(*b*) Selected specimens after forging or heat-treatment by the author.

Hadfield Research Number.	Group Number.	Analysis.			Photo-micrograph Number.	Treatment.	Hardness by Diamond Pyramid test. Brinell Scale.		Description of Microstructure.
		C. per cent.	per cent.	Fe. per cent.			As received.	After treatment.	
6	B 3	0·88	Au. 0·61	98·15	P.M. 24	Heated to 800° C. and cooled in air	234	270	GOLD STEEL. Lamellar pearlite and grains of ferrite. Similar to condition as received.
14	C 1–3	0·94	Pt. 0·74	97·60	P.M. 25	Forged from 9/16-inch by 1/2-inch to 3/16-inch by 3/16-inch cross section	230	350	PLATINUM STEELS. Lamellar pearlite. Pearlite was granular as received.
17	C 1–6	0·61	2·50	96·70	P.M. 26	Heated to 800° C. and cooled in air	330	325	Very fine granular pearlite, with traces of lamellar pearlite and of free ferrite. Similar to condition as received.
17	C 1–6	0·61	2·50	96·70		Heated to 800° C. and cooled in air. Heated to 1,100° C. and quenched in water	330	710	Moderately coarse acicular martensitic structure. No austenitic grains or free carbide.

TABLE V (continued).

(*b*) Selected specimens after forging or heat-treatment by the author (continued).

Hadfield Research Number.	Group Number.	Analysis.			Photo-micrograph Number.	Treatment.	Hardness by Diamond Pyramid test. Brinell Scale.		Description of Microstructure.
		C. per cent.	per cent.	Fe. per cent.			As received.	After treatment.	
									RHODIUM STEEL.
25	C 3–1	0·97	Rh. 1·50/1·60	97·50	P.M. 27	Heated to 800° C. and cooled in air	280	340	Very fine lamellar pearlite. Similar to condition as received.
25	C 3–1	0·97	Rh. 1·50/1·60	97·50	P.M. 28	Heated to 800° C. and cooled in air. Heated to 800° C. and quenched in water	280	735	Fine, slightly acicular groundmass. Very small spheroids of carbide distributed throughout the mass.
25	C 3–1	0·97	Rh. 1·50/1·60	97·50	P.M. 29	Heated to 800° C. and cooled in air. Heated to 1,100° C. and quenched in water	280	760	Moderately coarse acicular martensitic structure, with a few isolated austenitic grains. No free carbide remaining.
									GOLD-NICKEL STEEL.
22	C 2–2	1·06	Au. 0·75 Ni. 2·18	96·00	P.M. 30	Heated to 800° C. and cooled in air	300	315	Very fine lamellar pearlite. Similar to condition as received.

A.—Specimens examined in the condition as received by the author.

Considering the various groups in the order given, the following points seem worthy of mention.

(1) *Carbon Steels and Irons.*

Wrought Irons.—The microstructure of specimens 57/E.2–9 and 58/E.2–10 was typical of wrought iron, each containing a large number of slag inclusions, as illustrated in photomicro PM.1 of 57/E.2–9. A chemical determination of the proportion of phosphorus gave 0·124 and 0·128 per cent. respectively, which is about the usual amount found in wrought iron.

Specimen 26/C.3–2 showed irregular carburisation at the surface, due to some unknown cause, near two opposite corners of the rectangular cross section, as shown in photomicro PM.2. Otherwise the material resembles wrought iron.

Carbon Steels.—The microstructure of specimen 20/C.1–9 showed that it was not homogeneous. In a few small areas in the centre the only constituent was pearlite, and the proportion of carbon would, therefore, be about 0·9 per cent., but the structure of the rest was that of a 0·25 to 0·40 per cent. carbon steel. Fig. PM.4 shows a photograph of the complete cross section of this specimen at 2 magnifications in the centre of which the carbon segregation is clearly seen.

The remainder of the carbon steels, the photomicrographs of which are represented by figs. PM.5 and 6, call for no special comment.

High Sulphur Steel (Figs. PM.7 and 8).—Mention has also been made of the discovery of three specimens of this remarkably high sulphur material amongst FARADAY's specimens. The sulphide in steel 68/F.2, which contains 1·76 per cent. of sulphur, exists in globular aggregates and not in films, although the material contains only a trace of manganese. The complete disintegration into free cementite of the pearlite in this material of 1·75 per cent. of carbon is noteworthy.

(2) *Binary Steel Alloys.*

Chromium Steels, Nickel Steel, Copper Steel.—The microstructures of these specimens are quite typical of their classes and therefore call for no special comment. No. 24/C.2–4 (2·19 per cent. Ni) is illustrated in fig. PM.9, and No. 29/D.2 (2·79 per cent. Cu) in fig. PM.10, where the structure is seen to consist merely of lamellar pearlite.

Gold Steels.—The three examples show no feature which distinguishes them from carbon steels of the same proportion of carbon. It is inferred therefore that gold in quantities increasing to 0·90 per cent. does not appreciably alter the eutectoid proportion of carbon, and further, it is completely soluble in steel. A photomicro of No. 6/B.3 is shown in fig. PM.11.

Silver Steels.—The important feature of these specimens was the existence of the silver as a separate micro constituent. On first examining one of these specimens, some particles were noticed among the non-metallic inclusions, which became bright when the stage of the microstructure was racked a little out of focus. When in focus, the particles were mottled and of a yellow colour. In shape they were generally elongated. The chemical analysis had indicated that the specimen contained silver, and on etching the polished specimen with a solution of sodium sulphide, many particles among the inclusions were blackened. It may be noted that in specimen No. 4/B.1 containing only 0·13 per cent. of this metal, inclusions of silver were found. Fig. PM.12, which is a photomicrograph of specimen No. 12/C.1–1 polished, but unetched, shows a number of silver inclusions. It may be concluded therefore that the solubility of silver in high carbon steel is very low. Reference has already been made to the observations of FARADAY when melting silver with steel.

Platinum Steels (figs. PM.13 to 21).—In amounts up to 2·50 per cent., platinum has given no indication of its presence in the microstructure. Even in the specimen No. 31/D.4, containing only 0·07 per cent. of carbon and 2·25 per cent. of platinum, ferrite and non-metallic inclusions are the only micro-constituents visible (see fig. PM.20). Platinum at any rate in amounts up to about 2·5 per cent. is therefore soluble in either low or high carbon steel. The low carbon in this specimen No. 31/D.4 made it particularly interesting, giving rise to some speculation both as to the base used and the method of its manufacture. All that can be said on this point as a result of the micro-examination however is, that if, as seems probable from the high phosphorus content, it was made from wrought iron, then the major proportion of the slag inclusions present in the latter have been removed in the melting.

Specimens Nos. 41/E.1–1 and 43/E.1–3 possessed the characteristic structures of hardened steels, the remainder indicated the ordinary unhardened condition. Further reference is made to this point in describing the structure after heat treatment.

It is to be regretted that the specimen No. 17/C.1–6, fig. PM.21, containing the highest proportion of platinum, 2·50 per cent., was found to be severely decarburised at the surface, thus reducing its value for investigatory purposes. It was, however, submitted to an experimental quenching treatment, the results of which are described later.

Specimen No. 39b/D.12b was the first FARADAY specimen to be received for examination, and a general description of the microstructure has already been given in the special account of the investigation of this specimen. Partly because this was the first specimen examined, but also because the micro-examination showed the structure to be very much segregated, a series of photomicros were prepared from this specimen, and are shown on figs. PM.15 to 19. A detailed description of these photomicros will now be given.

Fig. PM.15 is a photomicro at 4·8 magnifications, illustrating the structure over the whole surface of one face of this small specimen, and clearly shows the laminated and heterogeneous character of the structure. This resolves itself into a number of zones, each of which has been lettered for the purpose of reference in the description of the subsequent photomicros taken at higher magnifications.

Fig. PM.16 illustrates the microstructure at 80 magnifications of Zone C, and consists of a dark groundmass of fine troosto-martensite and light striæ of acicular martensite with little spheroids of free carbide. The photomicro at 1200 magnifications, taken of an area in one of the white striæ above mentioned, is shown in fig. PM.19. The acicular character of the structure is more clearly seen at this magnification, as are also the little white spheroids of free carbide. The inclusion in the centre of the field is sulphide of iron.

Fig. PM.17 illustrates the structure of Zone A at 1200 magnifications, and is also typical of the dark etching constituent in Zones C and E. The structure consists of fine acicular troosto-martensite with traces of austenite (white).

Fig. PM.18 is of an area in Zone D, and is a beautiful example of acicular austenite and martensite. Examples of this structure are also found in the groundmass of Zone B.

The general character of the microstructure is that of a drastically quenched steel.

Rhodium Steels.—These specimens as illustrated by PM.22 show that rhodium in proportions up to about 1·50 per cent. has not affected the microstructure of high carbon steel when in the pearlitic condition. Rhodium is thus soluble to this extent at least. Some experiments on the effect of hardening treatments on the microstructure are described below.

(3) *Ternary Steel Alloys.*

Platinum-Silver Steel, Gold-Silver Steel.—Metallic silver was found as inclusions in both these specimens, otherwise there was nothing noteworthy in their microstructures. The gold-silver steel, No. 11/B.8, contained 0·88 per cent. of gold, and so little as 0·15 per cent. of silver. It might have been expected that owing to the solvent action which they themselves have on silver, the platinum or gold would have facilitated the solution of silver in the steel, but evidently this has not been so.

Gold-Nickel Steel.—The gold has caused no modification of the microstructure (see fig. PM.23).

Non-Metallic Inclusions.—It should be noted that the non-metallic inclusions found in the specimens examined in this research were generally attacked by sodium picrate. They were therefore chiefly sulphide inclusions. Since the alloys contained no manganese, the inclusions must have consisted of ferrous sulphide. They were grey-brown in colour, whereas manganese sulphide inclusions are dove-grey. Their amount was not excessive except in the high sulphur steels.

Segregation.—The specimens generally showed a marked degree of segregation resulting from the mode of primary solidification. Different areas are differently coloured or toned as a result of the attack of the etching reagent. The photomicros PM.15 and 16 of specimen No. 39b/D.12b at 4·8 and 80 magnifications are illustrative of the type of segregation met with in the Faraday steels.

B.—Specimens examined after Forging or Heat Treatment, in the author's laboratory.

Forging.—One specimen only was examined after experimental forging, a platinum steel, No. 14/C.1–3, containing 0·94 per cent. of carbon and 0·74 per cent. of platinum. As will be seen in fig. PM.25, although it suffered a 9 : 1 reduction in cross section, no significant change in the microstructure was produced as compared with fig. PM.13. It may, therefore, be concluded that the specimen when first received was in the forged condition also.

Heat Treatment.—In order to determine the effect of the various alloying elements, it is, of course, necessary to test the alloys under similar conditions of heat treatment. The microstructure of the specimens as received, in most cases suggested that the specimens had been cooled in air. A representative of each of the gold, platinum, rhodium, and gold-nickel alloys was therefore taken and submitted to the heat treatment known as " normalising," that is, heating to 800° C., allowing to attain equilibrium followed by cooling in the air. The small pieces used in this research were maintained for five minutes at 800° C. It will be seen from the Table V (B), and photomicros PM.24, 26, 27 and 30, that in every case the structure resulting from this treatment was similar to that in the condition as received by the author. It follows, therefore, that these particular alloys, which had a pearlitic microstructure, had in the final operation performed on them by FARADAY been cooled freely in the air from a temperature exceeding at least 800° C.

Effect of Hardening Treatments on the Microstructure.—It was decided to test also the hardening properties of two of the alloyed steels, as indicated by the microscope. Specimen 25/C.3–1, containing 0·97 per cent. of carbon and 1·50 per cent. of rhodium was selected as one of these, and three testpieces (*a*), (*b*), (*c*) cut from it of equal size. All were normalised, (*b*) was then heated to 800° C. and quenched in water, and (*c*) was heated to 1100° C. and quenched in water. The respective microstructures after these treatments, shown in figs. PM.27, 28 and 29, resembled those of a carbon steel having the same carbon content. Very few austenitic grains were to be seen in the structure of the small piece quenched from 1100° C.

The hardness was determined on the actual micro-section of each of the treated specimens, and the effects produced by the treatments were found to be consistent with the microstructure. It may, therefore, be stated that rhodium in proportions up to 1·5 per cent. is without effect on the microstructure of carbon steel after either slow or rapid cooling.

The other specimen selected was No. 17/C.1–6, which contained the highest amount of alloying noble metal of all, that is, 2·50 per cent. of platinum. Unfortunately, it was badly decarbonised, but this did not interfere with the single experiment carried out. This consisted of heating a specimen to 1100° C., followed by quenching in water. Both the microstructure and the hardness of the specimen after this treatment gave similar results to those which would be obtained with carbon steel of similar percentage of carbon under the same treatment, so that an addition of as much as 2·5 per cent. of platinum may be said to be without marked effect on the steel.

(*e*) *Resistance to Corrosion.*

Since it is known that one of Faraday's objectives in his research on alloy steels was to obtain a non-corrodible steel, or, at any rate, one which would make untarnishable mirrors, it seemed desirable to carry out such corrosion tests as were possible.

Such indications as exist in the records of any success Faraday may have had in this direction, point to their having resulted from the addition of platinum or rhodium, from which alloys, therefore, the author's selection was made for his own tests, including at the same time one of the plain carbon steels, No. 50/E.2–2 from the collection.

As a basis of comparison certain standard materials of known characteristics were necessary, and these were provided by specimens of mild steel of modern manufacture, and of a well-known brand of ingot iron. A complete list of the materials tested will be found in Table VI.

Table VI.—Tests for Resistance to Corrosion.

Exposure for 28 days to the atmosphere in the industrial district of Attercliffe, Sheffield. The specimens were previously heated to 750° C. and cooled in air.

Hadfield Research Number.	Group Number.	Analysis.				Brinell Hardness Number.	Loss in weight in gram per 100 sq. cms.	Nature of the Corrosion.
		C. per cent.	Mn. per cent.	per cent.	Fe. per cent.			
				Platinum Steels.				
43	E 1–3	1·20	—	Pt. 1·05	97·80	246	0·66	A small area in the centre of the underlying face was still bright. Rust rather more easily removed than from 31/D.4, and surface more coarsely pitted.
31	D 4	0·07	—	2·25	97·70	158/170	0·49	Underlying face completely covered with rust. Rust fairly difficult to remove. Surface very finely pitted.
17	C 1–6	0·61	—	2·50	96·70	280	0·66	Underlying surface rusted over. Rust easily removed. Surface very finely pitted.

TABLE VI.—Tests for Resistance to Corrosion (continued).

Hadfield Research Number.	Group Number.	Analysis.				Brinell Hardness Number.	Loss in weight in gram per 100 sq. cms.	Nature of the Corrosion.
		C. per cent.	Mn. per cent.	per cent.	Fe. per cent.			
Rhodium Steel.								
25	C 3–1	0·97	—	Rh. 1·60	97·50	278	0·66	Under surface completely rusted over. Rust easily removed, and surface very finely pitted.
Carbon Steel.								
50	E 2–2	1·52	—	—	98·16	232	1·22	Under surface rusted over. Rust fairly difficult to remove. Surface more coarsely pitted than that of 25/C.3–1.
Modern Steels, as forged (for comparison).								
“ Ingot Iron ”		0·03	0·08	—	—	89	1·04	Small area about $\frac{1}{4}$-inch square of underside bright, though marked with specks of rust. Not difficult to clean. Pitted not quite so coarsely as 50/E.2–2.
Mild Steel		0·11	0·39	—	—	114	1·16	Similar to “ Ingot Iron.”

Since physical condition plays a part in corrosion problems, all the specimens were first heat-treated alike, being heated to 750° C. for 15 minutes and cooled in air. The surfaces were cleaned of scale and polished, the pieces measured, dried in an air oven and weighed.

The specimens were exposed undisturbed for 28 days on the roof of the Hecla Works at Attercliffe, Sheffield, where experience has shown that the conditions are particularly severe. due to the industrial nature of the atmosphere.

After this exposure, the rust was removed by gentle rubbing with a soap of the type incorporating a hard powder, and the pieces were washed, dried and again weighed.

The results are given in Table VI, which displays the interesting fact that both platinum and rhodium additions to steel in the amounts to which they are present appreciably retard corrosion. The improvement effected here is not, however, sufficient to be of any practical value. That is, while it is possible that under ordinary conditions the tarnishing or rusting of instruments or mirrors made from these alloys might take somewhat longer than with carbon steels, FARADAY had by no means fully achieved with them his desired objective. Nevertheless, these results do suggest the possibility that, with appreciably larger percentages of platinum or rhodium, alloys having distinct claims to non-corrodibility might be obtained. It is, therefore, all the more to be regretted that the present collection does not contain any examples of the more highly alloyed steels made by FARADAY, specially, too, when it is remembered that it is only in the comparatively high percentages of 12 per cent. and over that chromium steels acquire a usefully non-corrodible character. The author hopes shortly to produce such experimental steels, for which Messrs. Johnson Matthey and Co. have most kindly agreed to supply the necessary platinum and rhodium. Experiments will then be made to determine this important point.

(*f*) *Specific Magnetism.*

The simple form of test for specific magnetism by the application of a hand magnet, devised by the author, and described in the joint paper by the late Professor H. K. ONNES, F.R.S., Dr. H. R. WOLTJER and himself "On the Influence of Low Temperatures on the Magnetic Properties of Alloys of Iron with Nickel and Manganese," read before the Royal Society in March, 1921,* could with certain adaptations be applied to several of the specimens, and, although the necessary modifications detracted from the accuracy obtainable, it was thought useful to do so.

For this test it is necessary to utilise standards similar in form to the testpieces employed. So far, therefore, as standards of known specific magnetism could be prepared similar to any of the FARADAY specimens, possessing one flat surface, these specimens could be tested as a whole without cutting them up. This naturally proved most convenient in the case of the uniformly shaped specimens of the "E" group.

The results of the tests are recorded in Table VII. In considering these the approximate character of the test must be recognised, as also the indefinite condition as regards heat treatment of most of the specimens. The fact, however, that none of the specimens in this research contains any large proportion of an alloying element is reflected in the generally high figures obtained for the specific magnetism, platinum apparently having no pronounced effect in lowering the figure.

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* 'Proc. Roy. Soc.,' A, vol. 99, 1921.

Table VII.—Specific Magnetism, as determined by the Pull of a Hand Magnet, of Specimens in the condition as received by the author.

Hadfield Research No.	Group No.	Analysis.				Specific Gravity.	Specific Magnetism.
		C. per cent.	per cent.	Pt. per cent.	Fe. per cent.		
41	E 1–1	1·12		0·90	97·50		91
42	E 1–2					7·82	93
43	E 1–3	1·20		1·05	97·80		98
44	E 1–4					7·79	90
45	E 1–5					7·80	100
46	E 1–6	0·94		1·15	97·60	7·84	100
47	E 1–7	1·30		1·10	97·30		91·5
48	E 1–8					7·84	96·5
49	E 2–1					7·78	96·5
50	E 2–2	1·52			98·16		91
51	E 2–3					7·79	95
52	E 2–4					7·70	94
53	E 2–5	1·50			98·40		90
54	E 2–6	1·47			98·30	7·80	92
55	E 2–7					7·80	98·5
56	E 2–8	1·48			98·27		96
			S.	P.			
57	E 2–9	0·12	0·027	0·124	99·65		100
58	E 2–10	0·07		0·128	99·20		100
59	E 2–11	1·45			98·20		100
			Ag.				
60	E 3–1	1·22	0·20		98·10		94
				Pt.			
61	E 3–2	1·33		0·80	97·65		98
62	E 3–3	1·05		1·40	97·34		95

(*g*) *Forging Properties.*

It had been possible to carry out the examinations so far made, on the specimens as a whole or on small pieces cut from them. There remained, however, certain desirable kinds of test requiring special forms of testpieces which, owing to their shape or relatively large size, could not be obtained in this manner except in an extravagant way.

Recourse was therefore made to forging down a sufficient portion of some of the specimens for this purpose. This, again, required very special consideration, for the following reasons. The practically complete absence of manganese did not promise well for the forging properties. It is true most of the specimens in the collection had actually been forged. The majority, however, showed imperfections, and although in many cases these could be removed before further forging, the material was apparently not of a forging quality sufficient to produce testpieces of the soundness required.

The drill holes in the " B " group of specimens made in order to obtain the necessary material for analysis further showed, in all cases, some cavities in the centre, which could scarcely be avoided in steel cooled, as this was, in the crucible.

The selection of specimens for these further tests was therefore very limited. Those actually forged were as follows, with a brief record of their behaviour. These were chosen as being the compositions of most interest among the specimens which were freest from visible imperfections. It was planned, where possible, to prepare a specimen 65 mm. in length for examination in the Chevenard differential dilatometer; from a portion of this a tensile testpiece could be obtained suitable for the tensometer apparatus.

Specimen No. 14/*C*.1–3 (*C.* 0·94, *Pt.* 0·74 per cent.).—A longitudinal seam and a few slight bursts on the edges of the original specimen were removed by the file.

The material forged easily and well to a length of 8½ inches of ¾-inch square section; forging commencing at 850/950° and finishing by swaging at a black heat. Three heatings were required.

After cutting off a length suitable for the dilatometer, and a piece ½ inch long for micro-examination, the remaining 5½ inches were examined for defects. A surface seam on one side was removed, as also some "shelliness" on the opposite side.

The piece was then further forged by flattening and edging down to about 0·07 inch by 0·25 inch, commencing at 850°. At this stage there was a burst about ½ inch long in the middle of one of the narrow edges. The material was therefore reheated, and flattened on each side of the centre to 0·027 inch in thickness.

The strip thus obtained was from 0·40 to 0·62 inch in width, and had a Brinell hardness of 340/360. To remove possible strains which might cause splitting in cutting up the strip, it was re-heated to 775° and cooled slowly, its hardness then being 190.

The strip was then parted down the centre, and four pieces 0·027 inch by 0·2 inch were obtained, of a total length of 19 inches. These strips were, as explained later, used in making the blades of some small knives.

After the Chevenard testpiece had been tested, a tensometer tensile testpiece was prepared from it by forging, as follows. The sounder end of the Chevenard piece was heated to 850° and upset by forging to 0·25 inch diameter. This portion was then cut off to a length of 1¼ inches, and similarly upset at its other end, producing a piece 1$\frac{1}{16}$ inches in length and apparently sound, suitable for machining a tensometer testpiece from.

The balance of the Chevenard testpiece was forged into strip and cut up into the small knife-blade section providing two pieces, 2 inches and 1 inch in length with difficulty, the material in this case tending to crack on the edges and ends in forging.

Specimen No. 17/*C*.1–6 (*C.* 0·61, *Pt.* 2·50 per cent.).—As previously explained, micro-examination of this specimen revealed decarbonisation to a depth of about 1¼ mm., confirmed by hardness determinations. After removing all this decarbonised material and any forging seams penetrating below it, the section remaining was very small, 0·35 inch by 0·25 inch. For reasons of economy of material, it was therefore decided to abandon, in this case, the idea of a Chevenard test, and prepare only a tensometer specimen and the small piece necessary for obtaining a heating and cooling curve of the inverse rate type.

For this purpose, a piece 0·55 inch long of the reduced section, weighing 6·5 grams, was cut off and forged gently at a commencing temperature of 900/950° down to

0·25 inch diameter. The piece obtained was 1¼ inches long, but showed a bad transverse burst ¼ inch from one end. This end was sawn off and used for the heating and cooling curve, the remainder, 1 inch in length, being allocated for the tensometer testpiece. The Brinell hardness as forged was 265.

Specimen No. 29/D.2 (*C* 1·05, *Cu* 2·79 per cent.).—From this specimen a piece 0·8 to 0·9 inch in length had been fractured off, and was therefore utilised for the forging.

This piece was variable in its Brinell hardness, from 390 to 710, and as a precautionary measure it was therefore softened by heating to 650° and cooling in air, the hardness then being 330. Seams on the faces and edges were filed and gouged out, and the edges rounded off.

Forging was commenced at 850/900°, and while the material behaved at first satisfactorily, in finishing to 0·22-inch diameter both ends commenced to burst, one rather badly. The length was just in excess of the 65 mm. required for a Chevenard test, and it was hoped that although imperfect, the specimen would serve for this purpose.

Specimen No. 9/*B*.6 (*C* 0·92, *Rh* 1·20, 1·14 per cent.).—It seemed specially desirable to have as complete a series of tests on one of the steels containing rhodium as possible. These were only three in number: No. 25/C.3–1 contained the highest percentage, 1·60, and was too small in size to obtain more tests than had already been taken. Of the two remaining specimens, Nos. 7/B.4 and 9/B.6, there was not much to choose on the score of soundness, but B.6 had the higher rhodium content, and was therefore chosen.

To obtain a specimen as sound as possible for forging, the centre cavities visible in the drill hole, and external surface roaks, were avoided by sawing out a piece from the material between the centre and the outside.

After filing up this piece on all faces, and gouging out any visible defects, the size was 0·55 by 0·36 by 0·85 inch, and its weight 18·6 grams.

This piece was forged at a commencing temperature of 850/900° down to 0·25 inch square, four re-heatings being required. On the finished piece there were many small cracks, some apparently superficial, others going in for a depth of $\frac{1}{16}$ inch. The piece, when squared at the ends to a length of 65 mm., was considered sufficiently satisfactory, however, for a Chevenard test (see fig. 7). Brinell hardness as forged, 255.

Specimen No. 22/*C*.2–2 (*C* 1·06, *Ni* 2·18, *Au* 0·75 per cent.).—The flat form of the section 13 × 4 mm. was not particularly suited to forging into small round or square bars, but in view of the interesting nature of its composition an attempt was made as follows.

On a length of 1½ inches some defects visible on the corners were removed by filing and gouging.

The piece was heated to about 800° and cornered by forging to a square section with light blows, during which the material appeared sound. After re-heating, the corners were rounded and with a further re-heating the piece was put through ¼-inch diameter swages. Longitudinal bursts then appeared, so the forging was stopped, the dimensions then being ¼-inch diameter by about 2¼ inches long.

The attempt to obtain a sound piece for tensile test in the tensometer having failed, it was decided to try and obtain a piece long enough for the dilatometer, of the standard size, $\frac{5}{32}$-inch diameter, even although it might be somewhat defective. The roaks in the $\frac{1}{4}$-inch round portion already prepared were therefore filed in an attempt to remove them, but they were so deep that several had to be left in, although then only appearing as fine cracks. This was after removing the material in some cases to a depth of 0·10 inch.

On reheating to 800/850° and attempting to forge further, the material burst along the seams with the first tap of the hammer, one piece falling away.

The best that could be done, therefore, was to cut a piece $\frac{3}{8}$-inch long from what was left of the forged $\frac{1}{4}$-inch round section, from which to obtain a heating and cooling curve of the inverse rate type. As recorded in the section on Tensile Tests, a tensometer testpiece was obtained in another way.

Specimen No. 57/*E*.2–9 (C 0·12, S 0·027, P 0·124, Fe 99·65 per cent.).—No difficulty was experienced in the forging of this specimen.

Forging commenced at 1100° C., the piece being rounded gently, then re-heated and swaged to $\frac{1}{4}$-inch diameter. After a further re-heating, swaging continued down to $\frac{5}{32}$-inch diameter, a length being obtained of 68 mm. suitable for a Chevenard specimen.

Generally, as regards the forging properties, it may be remarked that the steels containing platinum and rhodium appear to be quite readily forgeable, such difficulties as were met with being due to defects in the original specimens. No. 29/D.2, however, containing 2·79 per cent. copper, seems to be a steel which is difficult to forge successfully, this being in accordance with the author's own experience with high-percentage copper steel. On the other hand, steels with comparatively low percentages of copper can be forged and rolled without difficulty, but upon reaching 4 per cent. of copper such steels may be regarded as entirely unforgeable.

As regards specimen No. 22/C.2–2 (2·18 per cent. Ni and 0·75 per cent. Au), it is somewhat difficult to decide as to the merits of such a composition from the point of view of forging. Starting with a material of rather unsound character and of unsuitable section for the forging operations proposed, it would in any case have been difficult to guarantee satisfactory behaviour of the material even if of known good forging properties. The author is inclined, however, as the result of this experience, to believe that steel of this composition has not very good forging properties.

(*h*) *Determination of Critical Temperature Ranges.*

(i) *Dilatometric Method.*—For this purpose the dilatometric method was preferred because of the indications it gives of internal thermal changes being more complete than those provided by the usual heating and cooling curve indicating evolution or absorption of heat. The apparatus used was the differential mechanical dilatometer devised by M. PIERRE CHEVENARD and described by him in his article, "Dilatomètre Différentiel à Enregistrement Mécanique," published in "Revue de Métallurgie," 23^{e} année, No. 2 (Février, 1926, p. 92 a 99).

Forging the FARADAY specimens provided testpieces from Nos. 9/B.6, 14/C.1–3, 29/D.2 and 57/E.2–9. The first three being alloy steels, comparison pieces of plain carbon steel low in manganese, of modern manufacture and closely similar carbon content, were provided.

A uniform procedure was adopted, heating and cooling being controlled by a water rheostat operating on the heating furnace, at a fairly constant rate of 5 to 7 secs. per ° C. The maximum temperature was 950°. The first heating was from the "as forged" condition, and in all cases a repetition heating made as a check gave concordant results.

From considerations of space it is not possible to reproduce all the curves. The critical ranges indicated by them are, however, shown in Table VIII and only the curve for 9/B.6 (1·20 per cent. Rh) is reproduced in fig. 7.

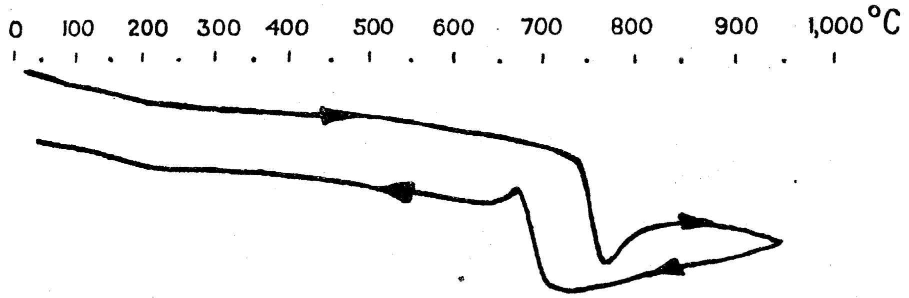


FIG. 7.—Chevenard Dilatometer Curves for Specimen No. 9/B.6.

These results show that rhodium to the amount of 1·14/1·20 per cent. has practically no influence on the critical temperature ranges of 0·9 per cent. carbon steel. 0·74 per cent. platinum, on the other hand, has lowered the critical ranges by about 30°. In addition, the actual ranges of temperature covered by the transformations show a tendency to extend, and the curves at the commencement of the critical ranges are rather more rounded, indicating a certain sluggishness in the transformations, due to the introduction of platinum.

Copper to the amount of 2·79 per cent. in specimen 29/D.2 also lowers the critical ranges under these conditions by about 20° on heating and 40° on cooling, again introducing some sluggishness into the transformations.

The curve obtained for 57/E.2–9, and the temperatures of its critical ranges are characteristic of those usually obtained for wrought iron.

In all the high carbon steels, whether plain or alloyed, the cementite change was observed uniformly at 210° to 220° on heating and cooling.

(ii) *Inverse Rate Curves.*—The specimens available for taking heating and cooling curves of the inverse rate type were 17/C.1–6 and 22/C.2–2. In addition 14/C.1–3 was included for comparison with the Chevenard curves on this specimen. The testpiece in these cases was very small, only about $\frac{1}{4}$-inch round or square and $\frac{3}{8}$ inch long, weighing 2 to 3 grams, and a hole was drilled most of the way down the axis to receive the platinum

TABLE VIII.—Critical Temperature Ranges of Steels made by FARADAY as shown by the Chevenard Differential Dilatometer. Also plain Carbon Steels of similar Carbon content for comparison.

The rate of Heating and Cooling was uniform at 5 to 7 secs. per ° C., thus requiring 1¾ hours to reach the maximum temperature of 950° C., and 1 hour to fall to 400° C.

Hadfield Research Number.	Group Number.	Analysis (per cent).						Critical Temperature Ranges.					
								Heating.			Cooling.		
								$Ac_{3,\ 2,\ 1}$.		Range.	$Ar_{3,\ 2,\ 1}$.		Range.
		C.	Si.	Mn.			Fe.	Commencement.	End.		Commencement.	End.	
Wrought Iron.													
57	E 2–9	0·12		Trace	S. 0·027	P. 0·124	99·65	Ac_2 775 Ac_3 915	— 945	— 30°	Ar_2 775 Ar_3 910	— 885	— 25°
Copper Steel.													
29	D 2	1·05			Cu. 2·79		96·30	735	755	20°	695	665	30°
Platinum Steel.													
14	C 1–3	0·94	0·33		Pt. 0·74		97·60	715	745	30°	700	655	45°
Rhodium Steel.													
9	B 6	0·92	0·33	Trace	Rh. 1·14 1·20		97·35	745	770	25°	715	680	35°
Modern Carbon Steels (for comparison).													
1991/2		0·97	0·13	0·12				750	770	20°	720	695	25°
1584 C/2		1·06	0·13	0·05				755	775	20°	730	705	25°

platinum-rhodium thermocouple. As with the dilatometric examination, comparison pieces of carbon steel low in manganese were provided.

Observations were taken in the usual way on a delicate reflecting pyrometer using a millimetre scale and recording the transits across each millimetre by chronograph. Uniform conditions of heating and cooling were adopted, the specimens reaching their maximum temperature of 850° C. in one hour, and cooling to about 600° C. in a further 40 minutes. After this, the transformations being completed, the rate of cooling was accelerated. Only the diagram for 14/C.1–3 (0·94 C., 0·74 Pt per cent.) is reproduced in fig. 8, the full data as to the transformations being recorded in Table IX.

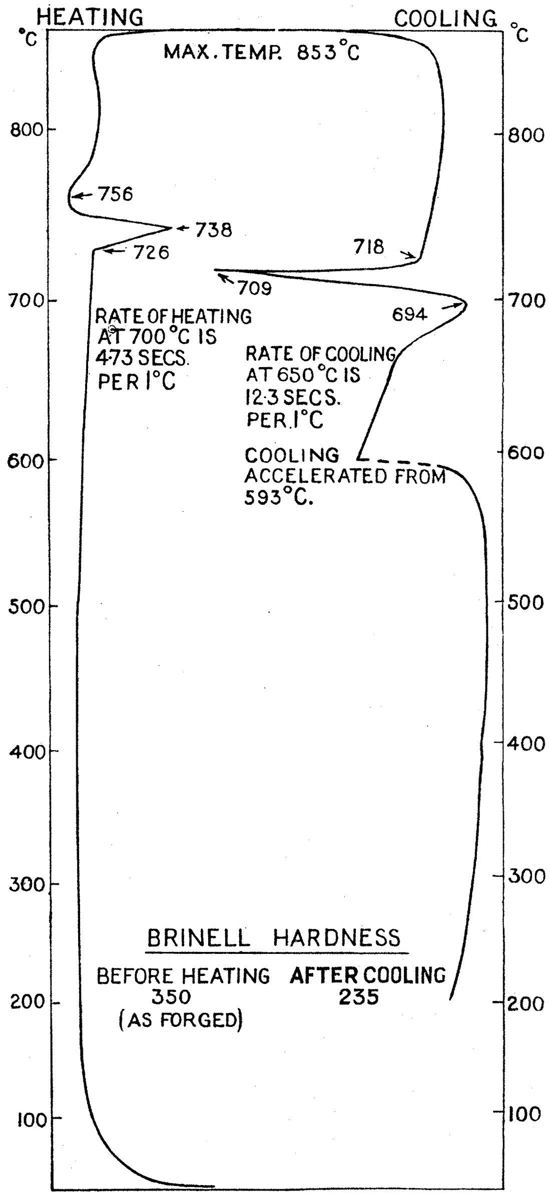


FIG. 8.—Heating and Cooling Curves for Specimen No. 14/C. 1–3.

TABLE IX.—Critical Temperature Ranges of Steels made by FARADAY as shown by Heating and Cooling Curves of the Inverse Rate Type. Also plain Carbon Steels of similar Carbon content for comparison.

The specimens were heated to a maximum temperature of 850° C. in one hour, and cooled to about 600° C. in 40 mins., the rate of cooling after this being accelerated.

Hadfield Research Number.	Group Number.	Analysis (per cent.).						Critical Temperature Ranges.					
								Heating.			Cooling.		
								$Ac_{3, 2, 1}$.		End.	$Ar_{3, 2, 1}$.		End.
		C.	Si.	Mn.			Fe.	Commencement.	Maximum.		Commencement.	Maximum.	
Platinum Steels.													
					Pt.								
14	C 1–3	0·94	0·33		0·74		97·60	726	738	756	718	709	694
17	C 1–6	0·61	0·05		2·50		96·70	723	731	752	700	691	674
Nickel-Gold Steel.													
					Ni.	Au.							
22	C 2–2	1·06	0·08		2·18	0·75	96·00	706	724	747	679	672	652
Modern Carbon Steels (for comparison).													
1991/2		0·97	0·13	0·12				740	*741–744	755	727	*718–720	710
1584 C/2		1·06	0·13	0·05				741	*742–744	757	727	*722–726	717

* Indicates decalescence on heating or recalescence on cooling.

The first heating was from the "as forged" condition, and a repetition heating was made in each case.

Specimen 17/C.1–6 should properly be compared with 1991/2 or 1584 C/2, and not with a 0·6 per cent. carbon steel, since the testpiece from 17/C.1–6 was prepared from the centre portion of the original specimen, while the drillings for analysis contained some of the decarbonised surface material, accounting for the low figure of 0·61 per cent. carbon. The carbon in the centre unaltered portion was not separately determined, but micro-examination shows it to be certainly above 0·9 per cent. As the data show, there is little change in the character of the heating and cooling curves of carbon steel above this percentage. Consequently either 1991/2 with 0·97 per cent. carbon, or 1584 C/2 with 1·05 per cent. carbon, will serve for comparison in this case.

The curves for 14/C.1–3 with 0·74 per cent. platinum provide confirmation of the Chevenard curves in showing some lowering of the critical ranges, not, however, so marked in the present case. The sluggishness introduced by the platinum also extends here the temperature range over which the transformations occur as compared with carbon steels.

In 17/C.1–6 with higher platinum content, 2·50 per cent., the same features are observed to a more marked degree, the critical ranges being lowered in temperature by 20° to 30°, and the ranges further widened.

With nickel 2·18 per cent. and gold 0·75 per cent. in specimen 22/C.2–2, there is a lowering of the critical ranges of about 40°, the ranges also being widened by about 20° ; both these facts are about what might be expected from the nickel addition alone, so that the gold has apparently had no material effect.

(*k*) *Thermal Expansion.*

It is one of the advantages of the dilatometric method of determining critical temperature ranges that it provides at the same time information as to the coefficients of thermal expansion at various temperatures. From the Chevenard curves, therefore, these coefficients were ascertained for the various specimens tested. Those concerned are 29/D.2 (2·79 per cent. Cu); 14/C.1–3 (0·74 per cent. Pt); 9/B.6 (1·20 per cent. Rh); with the carbon steels 1991/2 (0·97 per cent. C.) and 1584 C/2 (1·05 per cent. C.). In addition, the wrought iron specimen 57/E.2–9 and the wrought iron 4906 used for comparison.

As regards the high carbon steels, whether plain or alloyed, there is a remarkable uniformity in the results. These can all be expressed within close limits by the following figures, representing the coefficient of expansion in millionths per ° C.: at ordinary temperature, 11·0, 100°–11·5, 300°–14·0, 500°–16·5, and at 700° C. 16·0.

Possibly an exception should be made in the case of 29/D.2, the coefficients of which would be better represented by adding 0·5 to each of the above figures. The percentage of the added element is, of course, much higher in this case than in the others. It can be concluded, therefore, that neither copper, platinum, nor rhodium in comparatively small percentages has any marked effect on the coefficient of expansion of carbon steel.

The two wrought iron specimens give figures precisely similar to each other, but slightly different from those of the high carbon steels mentioned above, the figures being at ordinary temperature 12·0, at 100°–12·5, at 300°–14·0, 500°–16·0 and at 700°–15½.

(*l*) *Electrical Resistance.*

Upon the Chevenard testpieces it was possible to make a test of the specific electrical resistance. Though the test is necessarily approximate owing to the small size of the specimen, since little is known about the effect of such elements as platinum and rhodium upon steel in this connection, it was thought worth while. Specimen No. 29/D.2 had to be excluded, because, although its seaminess did not prevent a successful Chevenard examination being made, this unsoundness would undoubtedly affect the electrical resistance seriously.

The usual fall of potential method was employed, a steady current being passed through the specimen, through copper leads attached at the ends and through a standard manganin resistance. The fall of potential over this resistance, and, by means of bronze knife edges, over a measured length of the specimen well clear of the ends, was determined on a potentiometer. These measurements, in conjunction with the sectional dimensions of the specimens, enabled the specific resistance to be calculated, the figures being given in Table No. X.

Table X.—Specific Electrical Resistance.

Test specimens slowly cooled from 950° C.

Hadfield Research Number.	Group Number.	Analysis (per cent.).						Temperature of Test.	Specific Electrical Resistance. Microhms per c.c.
		C.	Si.	Mn.			Fe.		
Wrought Iron.									
57	E 2–9	0·12	—	Trace	S. 0·027	P. 0·124	99·65	18°	11·9
Platinum Steel.									
14	C 1–3	0·94	0·33	—	Pt. 0·74		97·60	20°	20·0
Rhodium Steel.									
9	B 6	0·92	0·33	Trace	Rh. $\left\{\begin{matrix}1{\cdot}20\\1{\cdot}14\end{matrix}\right\}$		97·35	18°	19·7
Wrought Iron and Modern Carbon Steels (for comparison).									
4906		0·02	0·14	Trace	S. 0·013	P. 0·013		18°	12·1
1991/2		0·97	0·13	0·12	S. 0·032	P. 0·032	—	23°	19·2

The electrical resistance of specimen No. 57/E.2–9 is evidently normal for wrought iron.

As regards the platinum and rhodium steels, the addition of these elements clearly has very little effect upon the electrical resistance of high carbon steel. Such a result is not altogether surprising, being in accordance with the general rule that the elements having the largest atomic volumes have the greatest effect. Platinum and rhodium have small atomic volumes.

(*m*) *Tensile Tests.*

By means of the ingenious little apparatus known as the tensometer, designed by Mr. L. H. Hounsfield, M.I.Mech.E., it was even possible to make actual tensile tests on some of the specimens, although they are so small. With this apparatus tests can be carried out and full tensile data obtained from a specimen of the very small dimensions shown in the sketch, fig. 9, and weighing (in steel) less than 4 grams. In addition, an autographic attachment enables a stress-strain diagram up to the point of fracture to be obtained.

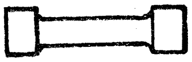


FIG. 9.—Sketch of Tensometer Testpiece (full size).

As mentioned in the section on Forging, pieces suitable as blanks for tensometer testpieces were obtained by forging from specimens No. 9/B.6, No. 14/C.1–3, No. 17/C.1–6, the first two being obtained from a portion of the Chevenard dilatometer testpiece. In the case of No. 22/C.2–2, as there appeared to be sufficient thickness in the unforged portion of the specimen, a piece 1⅛ inches long by ¼ inch wide was sawn out from the middle, thus leaving its contour undisturbed. This, however, did not provide a completely satisfactory specimen, the testpiece having marks on its machined surface due to a depression in the surface of the original specimen.

All four testpiece blanks were normalised by heating to 800° C. and cooling in air, before machining to pattern.

For comparison, similar testpieces were prepared from the high carbon steels of modern manufacture, of which previous use had been made in connection with the examination of the critical ranges.

The test results are given in Table No. XI. A stress-strain diagram was obtained in each case, that for specimen No. 14/C.1–3 being reproduced in fig. 10.

Specimen No. 14/C.1–3 with 0·74 per cent. platinum, it will be seen, has a somewhat high tenacity (60·5 tons per square inch) as compared with the high carbon steel 1991/2 of similar carbon content (58·0 tons). Its yield point is also higher, 33 tons against 29. At the same time the elongation and reduction of area are precisely the same as those of the carbon steel. Platinum to this amount, 0·74 per cent., therefore, as shown by this test, effects a slight but distinct improvement in the tensile properties of high carbon steel. It would have been most interesting, had sufficient material been available, to test this point further on quenched and tempered specimens.

The piece from No. 17/C.1–6 (2·50 per cent. Pt) unfortunately broke prematurely at a load of 38·5 tons per square inch, and when the elongation had only reached

TABLE XI.—Tensile Tests on specimens 0·159 inch diam. in the Tensometer Testing Machine. Material previously cooled in air from 800° C.

Hadfield Research Number.	Group Number.	Analysis (per cent).						Tensile Test.					Brinell Hardness Number.
		C. Per cent.	Si. Per cent.	Mn. Per cent.	Per cent.	Per cent.	Fe. Per cent.	Yield Point. Tons/ sq. in.	Maximum Stress. Tons/ sq. in.	Elongation. Per cent.	Reduction of Area. Per cent.	Fracture.	
Platinum Steels.													
					Pt.								
14	C 1–3	0·94	0·33		0·74		97·60	33	60·5	12·5	32	Fine cryst. with about 5 per cent. fibrous.	275
17	C 1–6	0·61	0·05		2·50		96·70	37	38·5	1·25	1·50	Fine cryst. Defective.	275
Rhodium Steel.													
					Rh.								
9	B 6	0·92	0·33	Trace	1·14 1·20		97·35	22·5	61·0	8·75	19	Medium cryst. with about 10 per cent. gran. Sound.	275
Nickel-gold Steel.													
					Ni.	Au.							
22	C 2–2	1·06	0·08		2·18	0·75	96·00	40	54·5	2·5	3	Fine grey gran. Sound. Test - piece fractured at a surface blemish.	300
Modern Carbon Steels (for comparison).													
1991/2		0·97	0·13	0·12				29	58·0	12·5	32	Cryst. Fibrous centre.	258
1584 C/2		1·06	0·13	0·05				28·5		13·75	33	Granular	235

1·25 per cent. This was clearly traceable to a defect visible in its fracture. It will be remembered that special difficulty had been experienced in the preparation of this testpiece, and, although an apparently sound portion had been cut for the purpose from the rather defective forging obtained, it was evidently not so sound as it seemed.

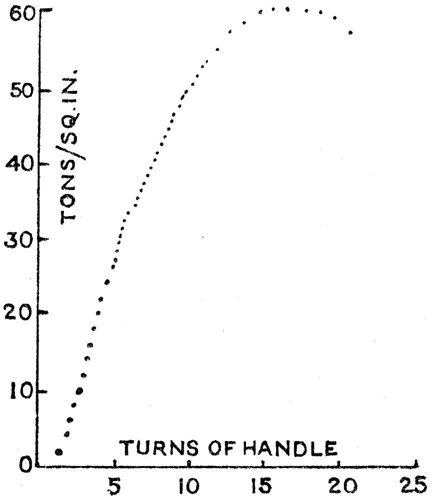


FIG. 10.—Tensometer Stress-Strain Diagram for Specimen No. 14/C.1–3.

The addition in specimen No. 9/B.6 of 1·20 per cent. rhodium has raised the tenacity slightly, but there is a more than commensurate falling off in the ductility. At the same time, the yield point is quite definitely lowered from 29 to 22·5 tons per square inch, as compared with unalloyed carbon steel. Rhodium, therefore, unlike platinum, has had a detrimental effect on the tensile properties.

Although the testpiece from No. 22/C.2–2 (2·18 per cent. Ni, 0·75 per cent. Au) bore a blemish which was likely to interfere with its displaying the true properties of this material, the test was carried out, fracture occurring at the defect with an elongation of only 2·5 per cent. after a load of 54·5 tons per square inch had been reached. Clear indication of the yield point was obtained at 40 tons, showing a considerable increase as compared with the corresponding carbon steel 1584 C/2, the yield point of which is 28·5 tons.

The Brinell hardness of 300 would indicate a true tenacity of about 65 tons per square inch, as compared with 51 tons for the carbon steel, so that while it is not possible to determine the full effect of the nickel and gold additions upon the tensile properties, it is clear that there is a very marked increase in the yield point and tenacity.

§ 9.—PREPARATION OF KNIVES FROM FARADAY'S STEEL.

From the FARADAY steel specimen No. 14/C.1–3, containing 0·94 per cent. carbon and 0·74 per cent. platinum, flat section strips were forged by the author, and from these were prepared twenty miniature knives. These were made by the famous Sheffield firm of cutlers, Messrs. Joseph Rodgers & Sons, Ltd., to whom the author takes this opportunity of offering his best thanks for the great amount of care and attention they have bestowed in the production of these remarkable knives from this platinum steel produced more than a hundred years ago.

The author felt that in the year devoted to the celebration of FARADAY'S work it would be appropriate if these souvenir knives could be prepared from steel actually made by FARADAY. The actual quantity of steel used was only 23 grams, or less than one ounce.

The finished knives represent steel which has been forged three times, first by FARADAY, then by the author, and finally by Messrs. Joseph Rodgers & Sons, Ltd. Though for want of steel naturally only miniatures, their construction and method of manufacture are in every way similar to those used for a Sheffield pocket knife of normal size, and with the same skilled workmanship which has been continued from the time of Chaucer, when the famous poet, in his "Canterbury Tales," related of one of his characters that "A Shefeld thwytel bare he in his hose." The blades of the knives are hardened and tempered, and within the limitations of their size quite capable of giving a good account of themselves.

The preparation of the strip of steel, 0·027 inch by 0·20 inch, from which the blades were made, has already been described in the section on Forging. The selection of the steel used from specimen No. 14/C.1–3 was determined because it contained platinum.

To test the hardening qualities of the steel, a small portion of the trimming from the edge of the strip was heated to 750° for two minutes and quenched in water. The steel was fully hardened, showing a Brinell hardness of 710, confirming the expectations derived from the dilatometric examination. This indicated no essential difference in behaviour of the platinum steel, as compared with carbon steel of similar carbon content. In the preparation of the knife blades no change was therefore found necessary, as compared with the normal practice.

The microstructure of this steel is shown in two photomicros, No. P.M. 13, representing the steel as forged and left by FARADAY, and No. P.M. 25, after being forged by the author.

The heating and cooling curve is shown by fig. 8 (p. 284).

§ 10.—CONCLUSION.

In conclusion, it is hoped that the present research has enabled valuable information to be obtained and put on record, also that the knowledge so gained will be of general service.

The author wishes to express his gratitude to the Chairman, Sir ROBERT ROBERTSON, F.R.S., and the Board of Managers of the Royal Institution for their generous permission in placing these FARADAY specimens of "Steel and Alloys" at the author's disposal to carry out this research. He also begs to thank Sir WILLIAM BRAGG, F.R.S., Director of the Laboratory, Superintendent of the House and Fullerian Professor, who occupies the same high posts so long held by FARADAY himself, for the very kind help he has rendered and the interest shown in this research; also his staff, including Mr. THOMAS

MARTIN, M.Sc., General Secretary; Mr. W. J. GREEN, B.Sc., Assistant in the Laboratory; and Mr. RALPH CORY, the Librarian.

Further acknowledgment is due in regard to the help rendered by the staff of the Royal Society, including the Assistant Secretary, Mr. F. A. TOWLE; Mr. R. WINCKWORTH, M.A., the Librarian; and Mr. H. W. ROBINSON, Assistant Librarian, in getting together much literature of the past containing the historical references required by the author and of which quite a number have been found of service.

In a research of this difficult nature, covering so much ground, a large amount of help has been necessary, and the author acknowledges with gratitude the willing assistance afforded by Mr. W. J. DAWSON, Metallurgical Director of Messrs. Hadfields, and the staff of their Research Laboratory, including Mr. T. G. ELLIOT, F.I.C., and his assistants, Messrs. WILLEY, F.I.C., A.R.S.M., WEST and ARNOLD, with regard to the chemical and metallographic examination; Mr. S. A. MAIN, B.Sc., F.Inst.P., who, as regards the mechanical, physical and many other tests was assisted by Mr. T. H. BURNHAM, B.Sc., and Messrs. TODD, SPILLER and STEVENSON.

With so many specimens to examine, the work carried out has been long and arduous. Nevertheless, the help offered at all times has been most cheerfully rendered. To one and all the author expresses most cordial thanks.

EXPLANATION OF PLATES 4–7.

PLATE 4.

FIG. 1.—The Box containing the FARADAY Specimens of "Steel and Alloys."

FIG. 2.—The seventy-nine Steel Specimens from the Box shown in fig. 1.

PLATE 5.

FIG. 4.—The Laboratory used by FARADAY.

PLATES 6 and 7.

FIGS. 5 and 6.—Group Arrangement of the seventy-nine Steel Specimens from the Box shown in fig. 1 (Sections 1 and 2).

PLATES 8–12.—PHOTOMICROGRAPHS.

	Photomicrograph Number.	Specimen Number.
PLATE 8.	P.M. 1.	57/E. 2–9.
	P.M. 2.	26/C. 3–2.
	P.M. 3.	20/C. 1–9.
	P.M. 4.	
	P.M. 5.	33/D. 6.
	P.M. 6.	56/E. 2–8.
	P.M. 7.	68/F. 2.
	P.M. 8.	
PLATE 9.	P.M. 9.	24/C. 2–4.
PLATE 9.	P.M. 10.	29/D. 2.
	P.M. 11.	6/B. 3.
	P.M. 12.	12/C. 1–1.
	P.M. 13.	14/C. 1–3.
	P.M. 14.	2/A. 2.
PLATE 10.	P.M. 15–19.	39 B/D–12 B.
PLATE 11.	P.M. 20.	31/D. 4.
	P.M. 21.	17/C. 1–6.
	P.M. 22.	25/C. 3–1.
PLATE 11.	P.M. 23.	22/C. 2–2.
	P.M. 24.	6/B. 3.
PLATE 12.	P.M. 25.	14/C. 1–3.
	P.M. 26.	17/C. 1–6.
	P.M. 27.	25/C. 3–1.
	P.M. 28.	25/C. 3–1.
	P.M. 29.	25/C. 3–1.
	P.M. 30.	22/C. 2–2.

Fig. 1.—The deal box, 9" × 5½" × 5¼", in which the specimens of steel were found.

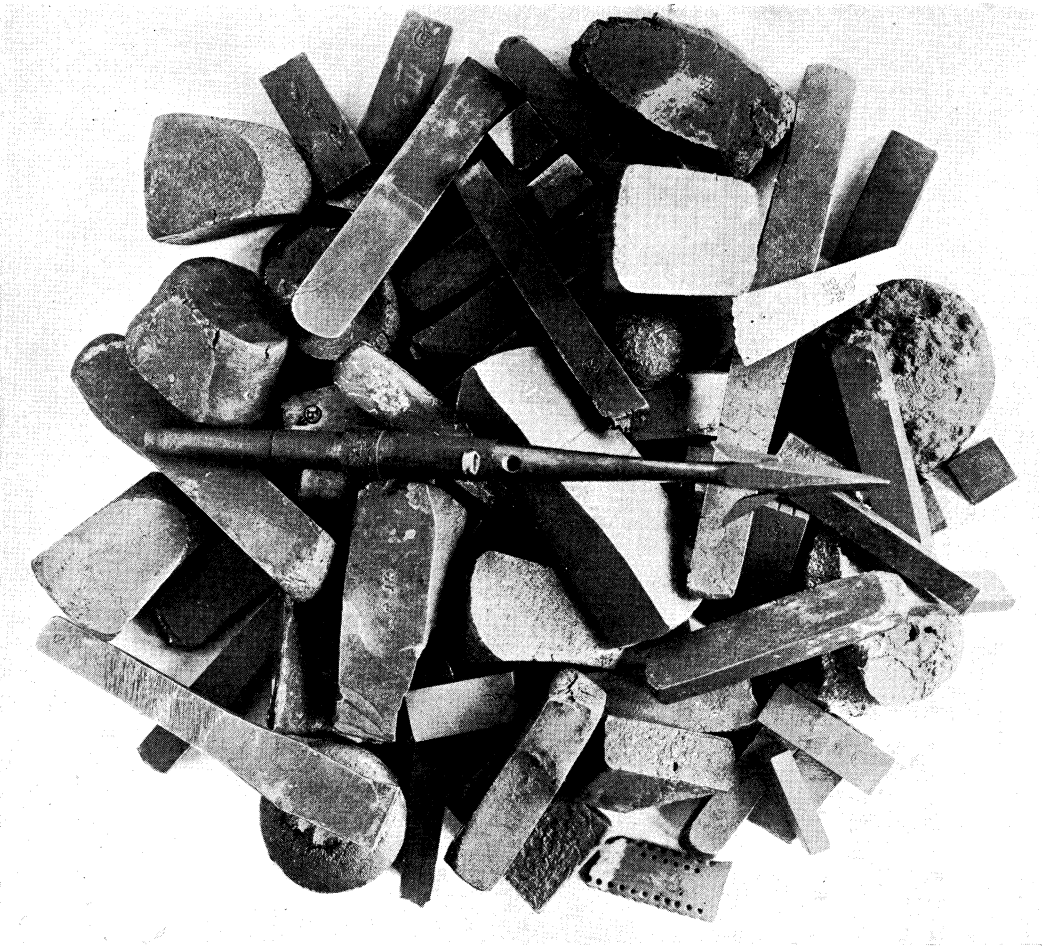


Fig. 2.—The 79 steel specimens taken from the box shown in fig. 1.

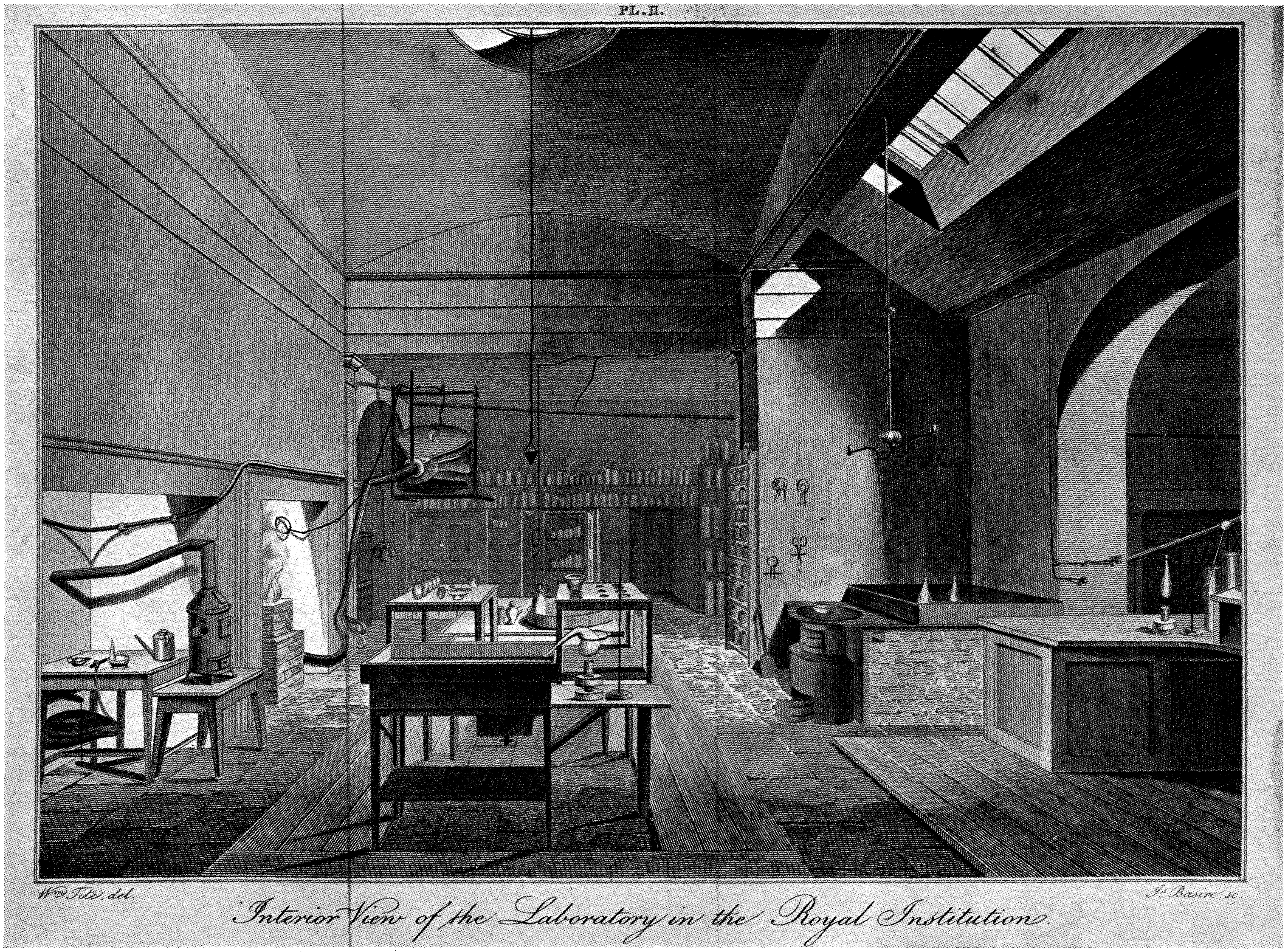


Fig. 4.—The Laboratory at the Royal Institution, as it was in Faraday's time: from Brande's "Manual of Chemistry," 1819.

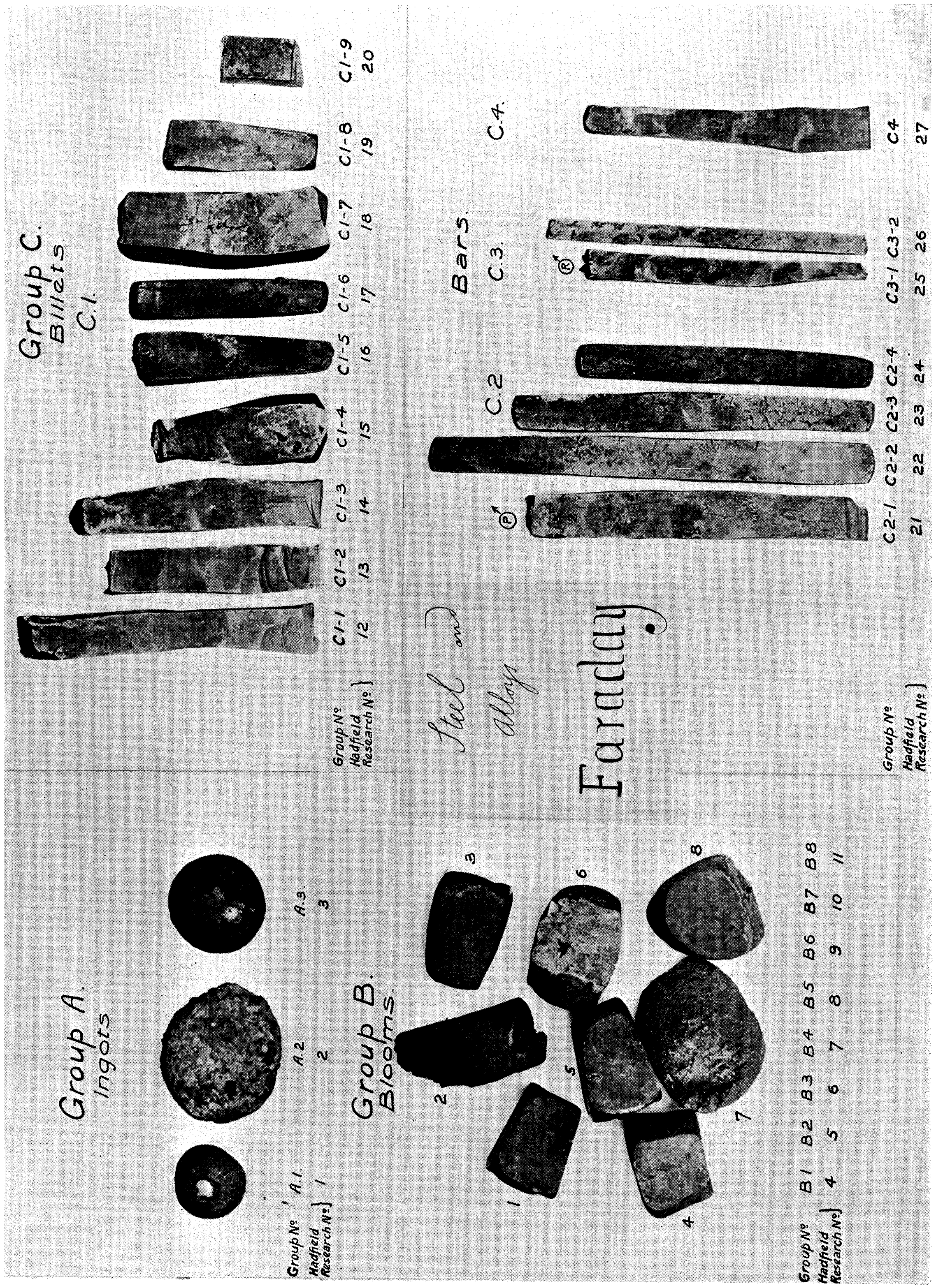

Group A.
Ingots
Group No
Hadfield Research No
A.1 1
A.2 2
A.3 3
Group B.
Blooms.
Group No
Hadfield Research No
B1 4
B2 5
B3 6
B4 7
B5 8
B6 9
B7 10
B8 11
1
2
3
4
5
6
7
8
Group C.
Billets
C.1.
Group No
Hadfield Research No
C1-1 12
C1-2 13
C1-3 14
C1-4 15
C1-5 16
C1-6 17
C1-7 18
C1-8 19
C1-9 20
Steel and Alloys
Faraday
Bars.
C.2
C.3.
C.4.
Group No
Hadfield Research No
C2-1 21
C2-2 22
C2-3 23
C2-4 24
C3-1 25
C3-2 26
C4 27
P
R

Fig. 5.

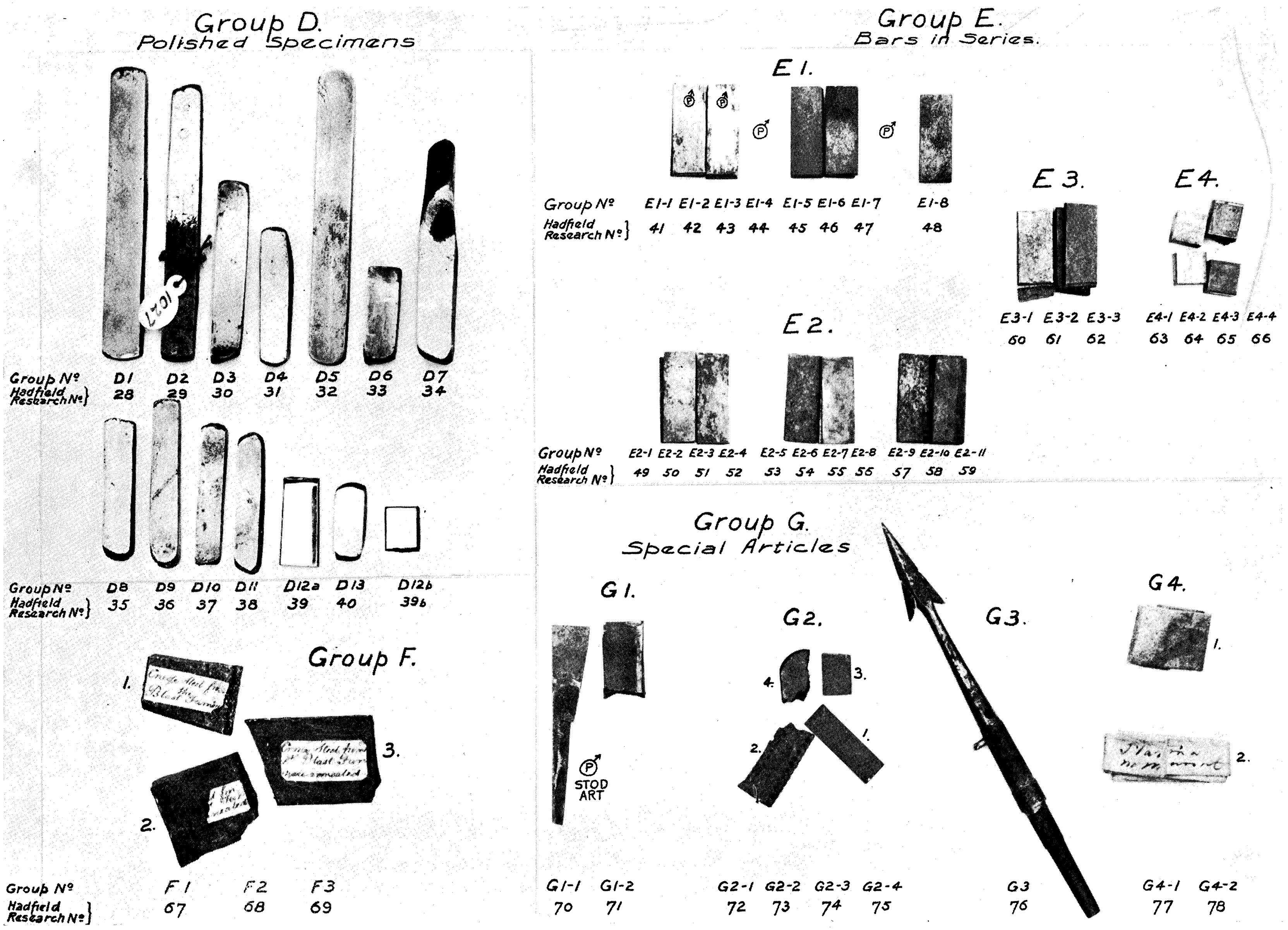
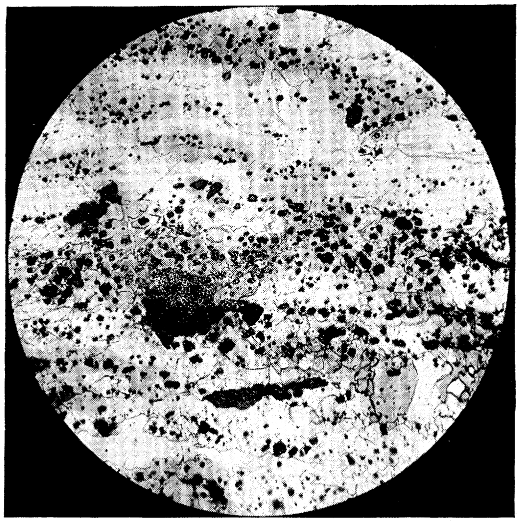
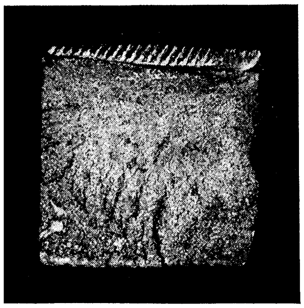

Group D.
Polished Specimens
Group Nº
Hadfield Research Nº
D1 28
D2 29
D3 30
D4 31
D5 32
D6 33
D7 34
1027
D8 35
D9 36
D10 37
D11 38
D12a 39
D13 40
D12b 39b
Group F.
1.
2.
3.
F1 67
F2 68
F3 69
Group E.
Bars in Series.
E1.
P
E1-1 41
E1-2 42
E1-3 43
E1-4 44
E1-5 45
E1-6 46
E1-7 47
E1-8 48
E2.
E2-1 49
E2-2 50
E2-3 51
E2-4 52
E2-5 53
E2-6 54
E2-7 55
E2-8 56
E2-9 57
E2-10 58
E2-11 59
E3.
E3-1 60
E3-2 61
E3-3 62
E4.
E4-1 63
E4-2 64
E4-3 65
E4-4 66
Group G.
Special Articles
G1.
P STOD ART
G1-1 70
G1-2 71
G2.
1.
2.
3.
4.
G2-1 72
G2-2 73
G2-3 74
G2-4 75
G3.
G3 76
G4.
1.
2.
G4-1 77
G4-2 78

Fig. 6.



PM. 1. (X 80).

PM. 2. (X 12).



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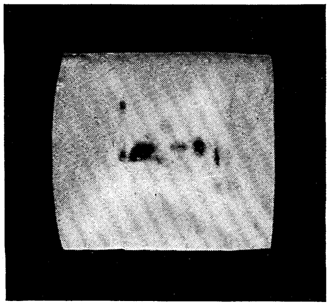

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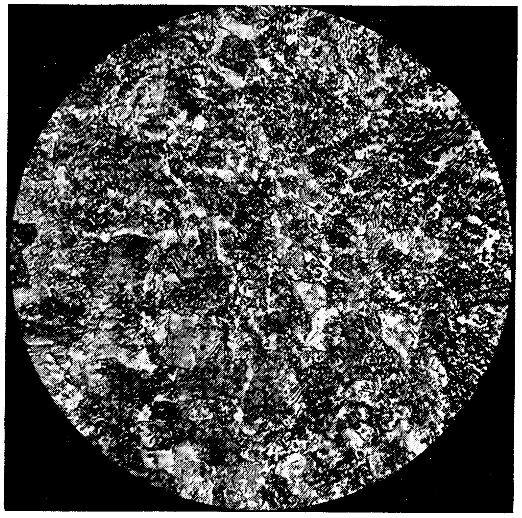

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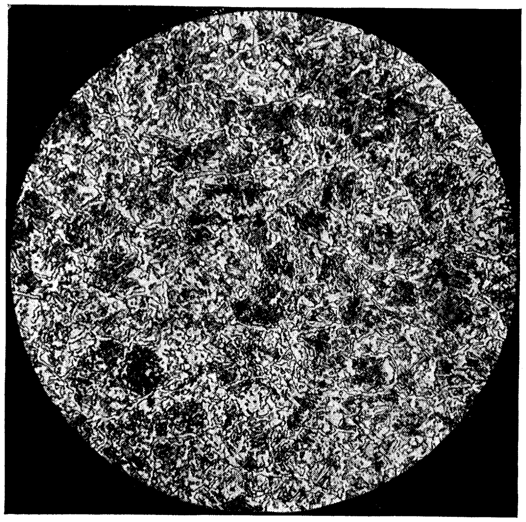

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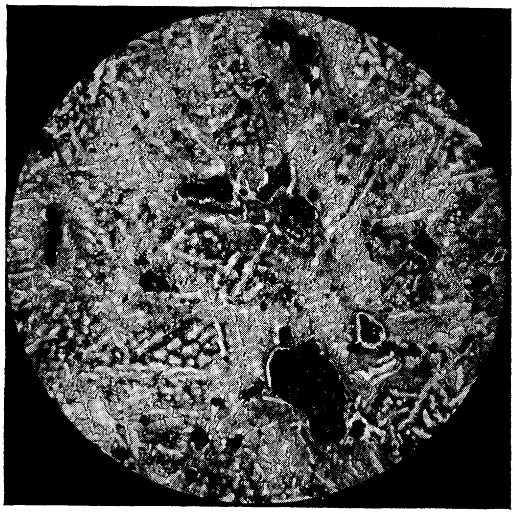

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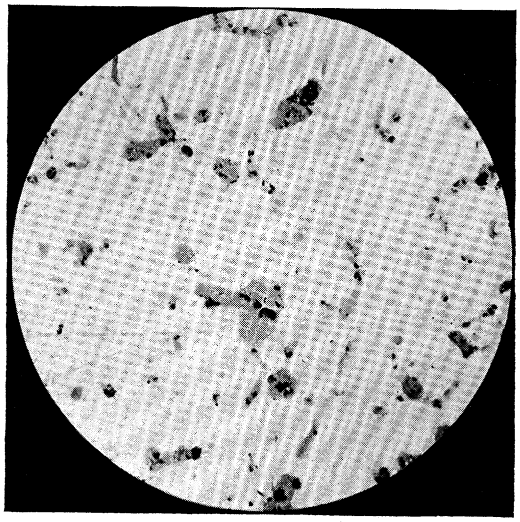

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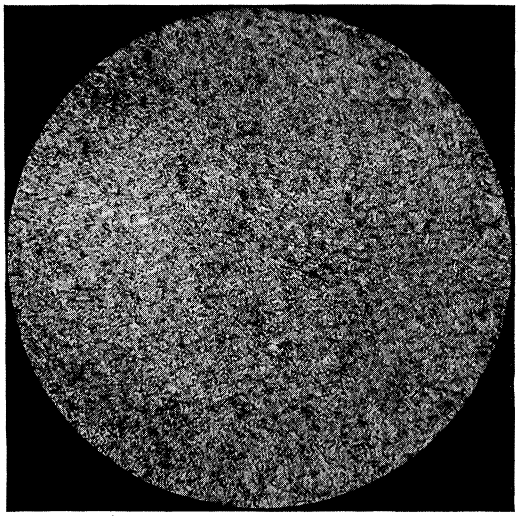

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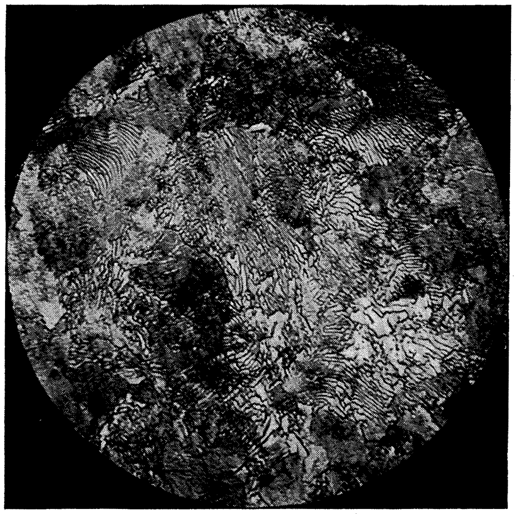

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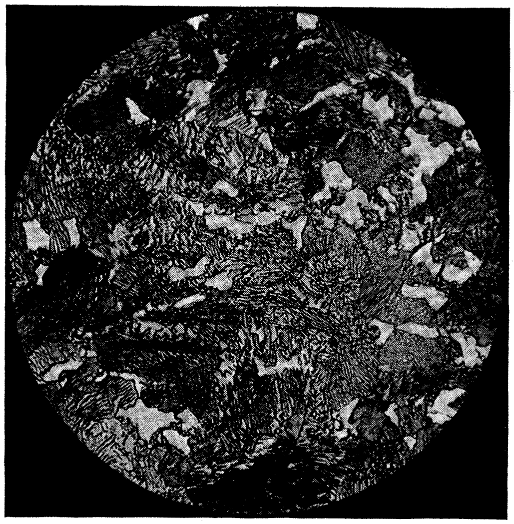

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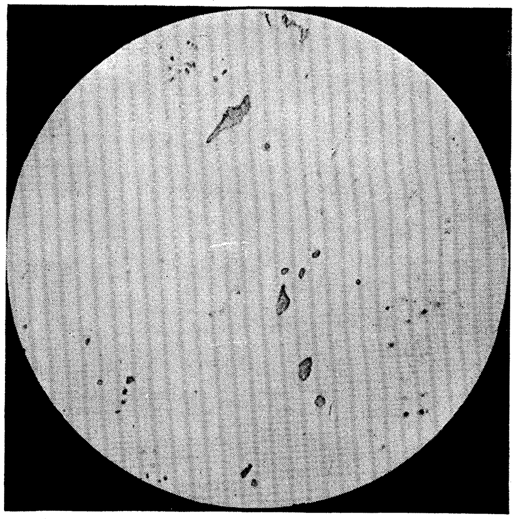

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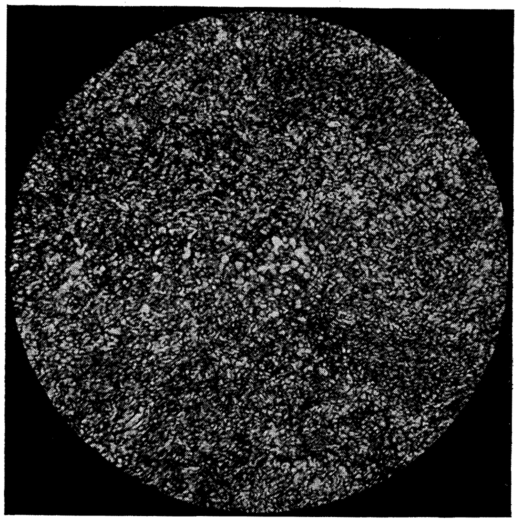

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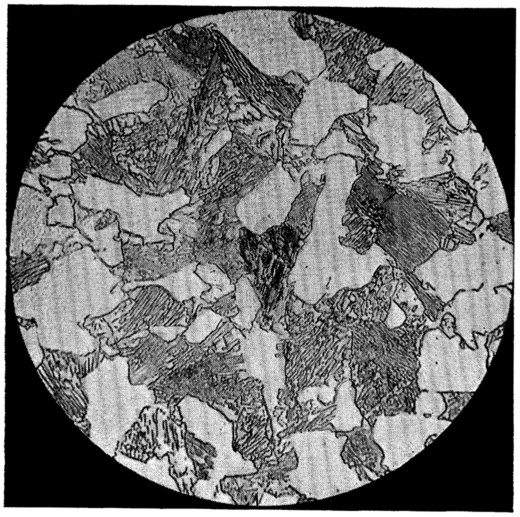

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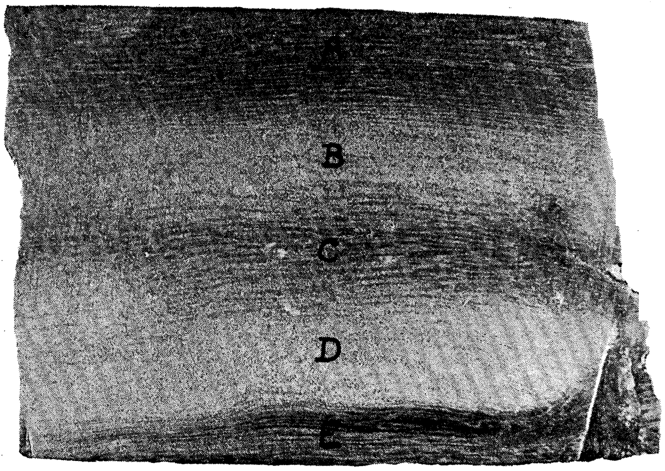

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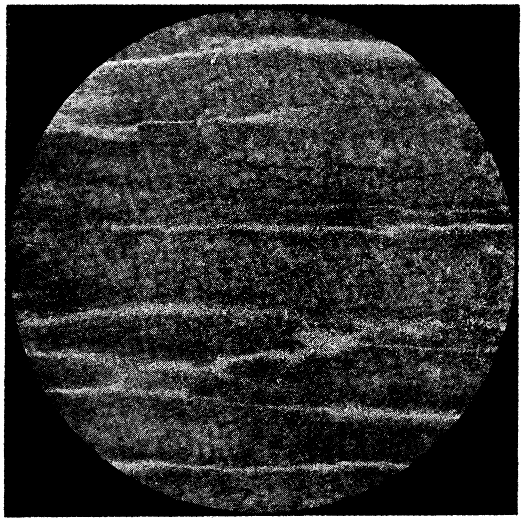

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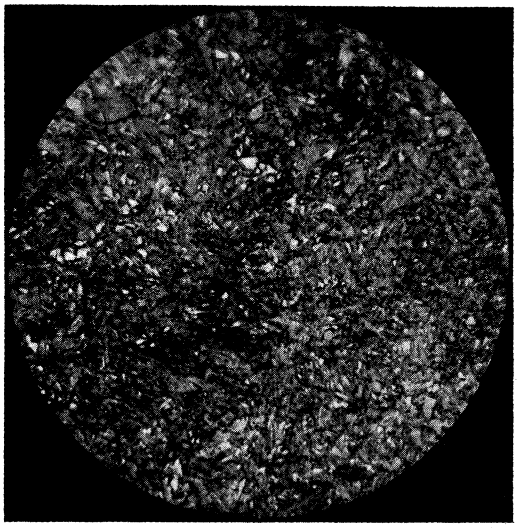

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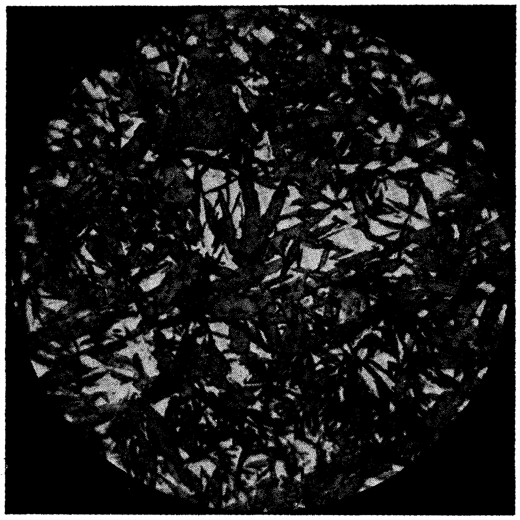

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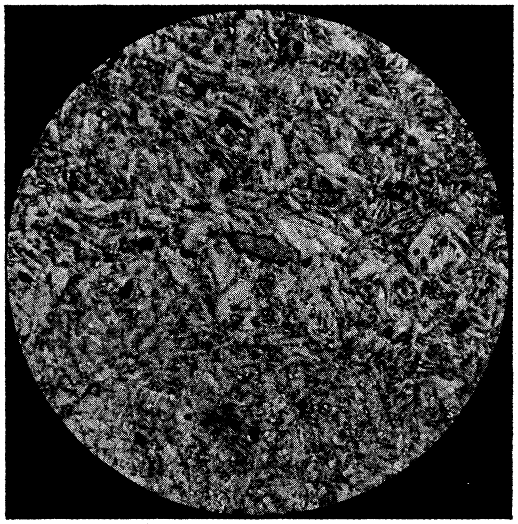

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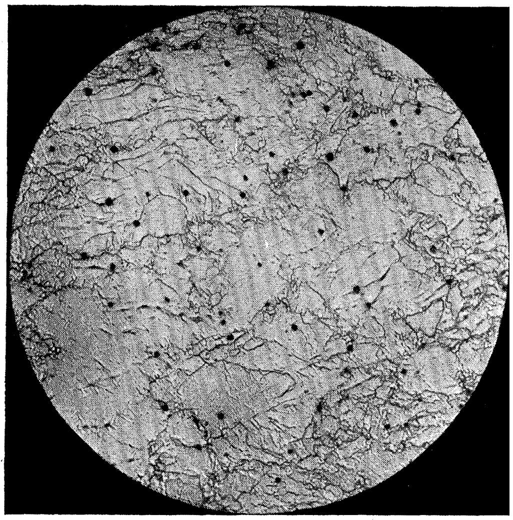

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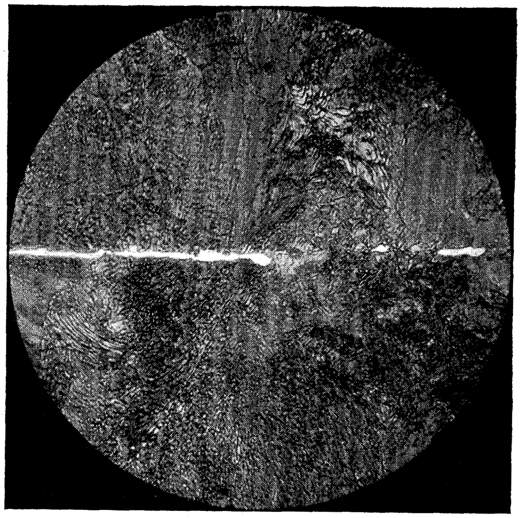

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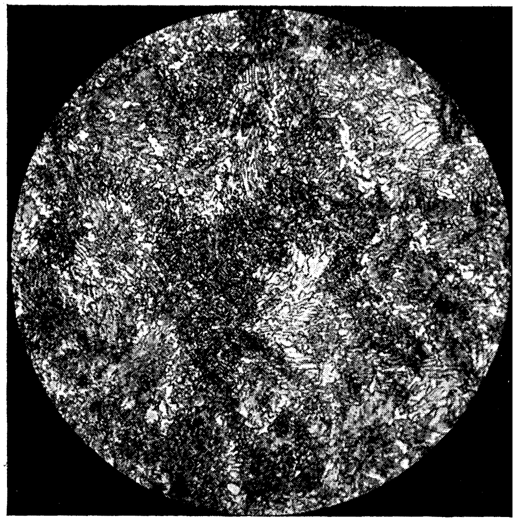

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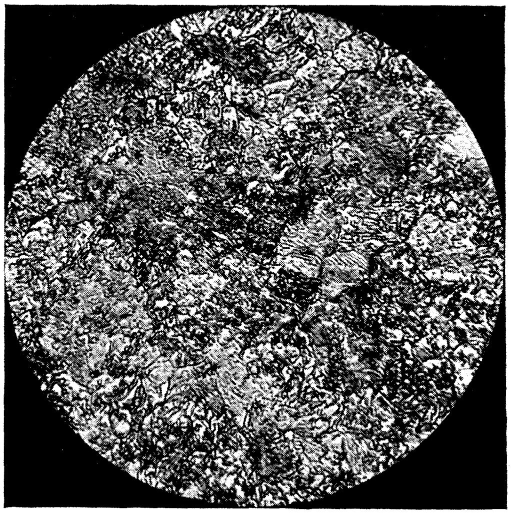

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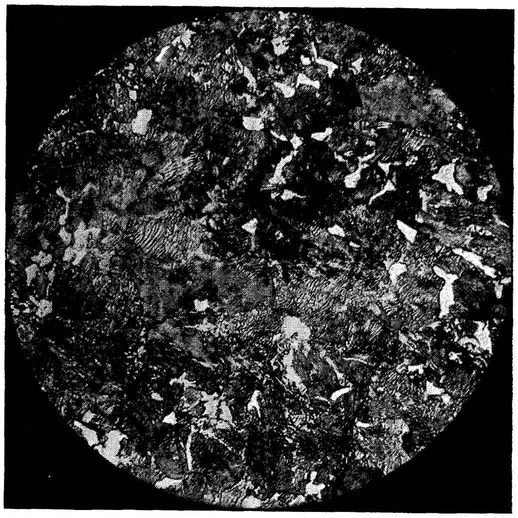

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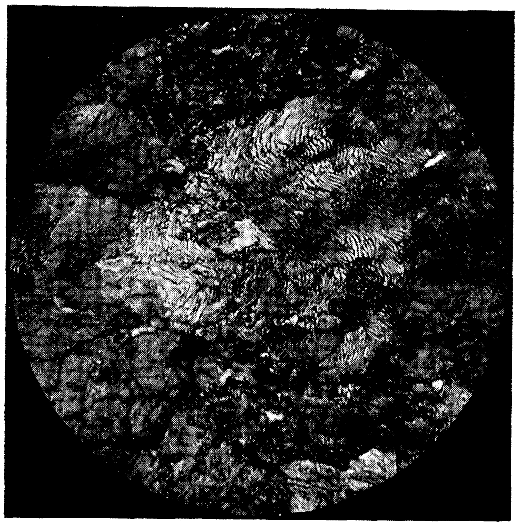

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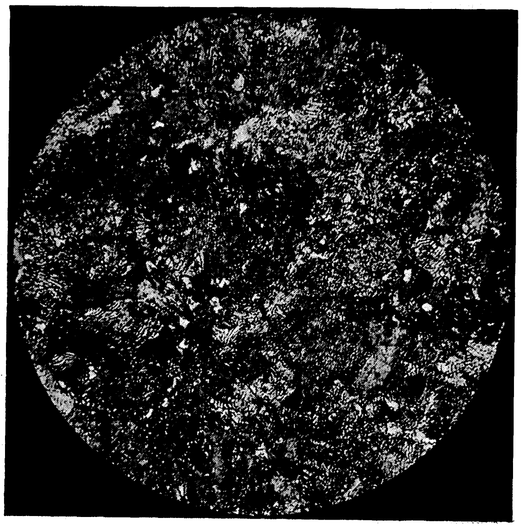

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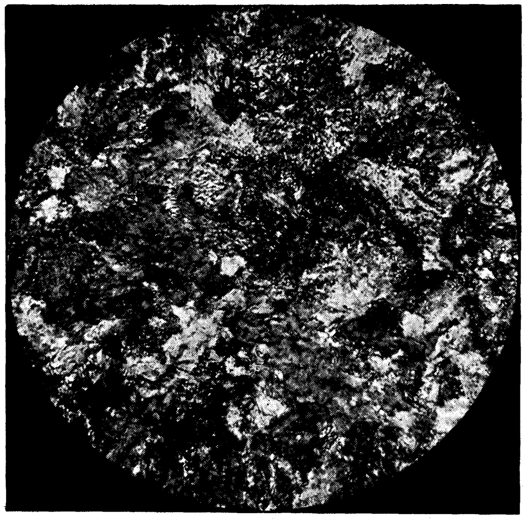

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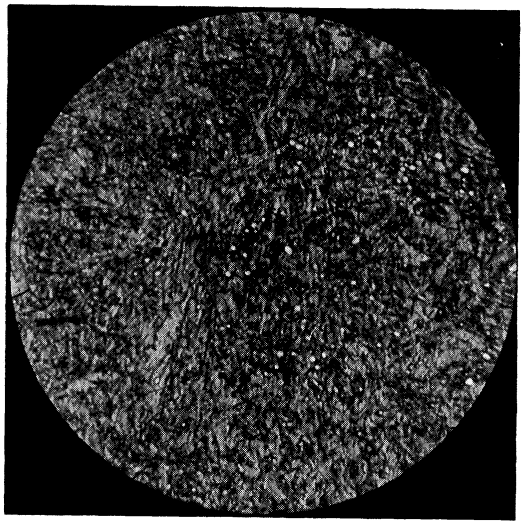

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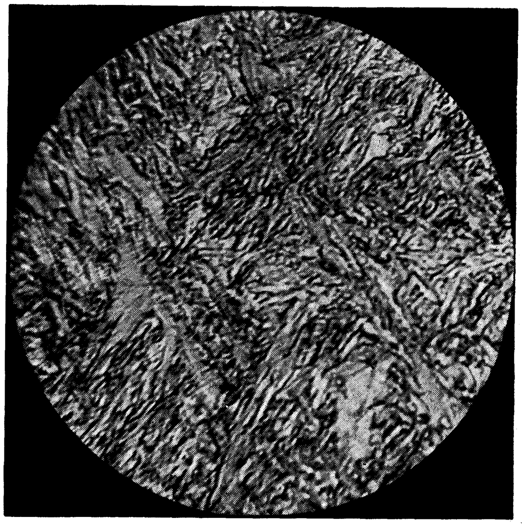

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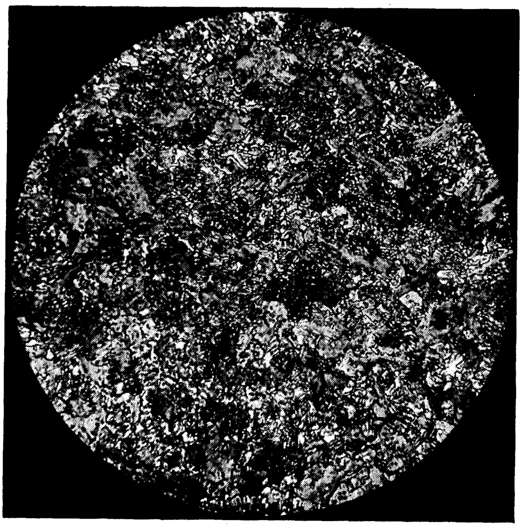


PM. 30. (X 400).

Fig. 1.—The deal box, $9'' \times 5\frac{1}{2}'' \times 5\frac{1}{4}''$, in which the specimens of steel were found.

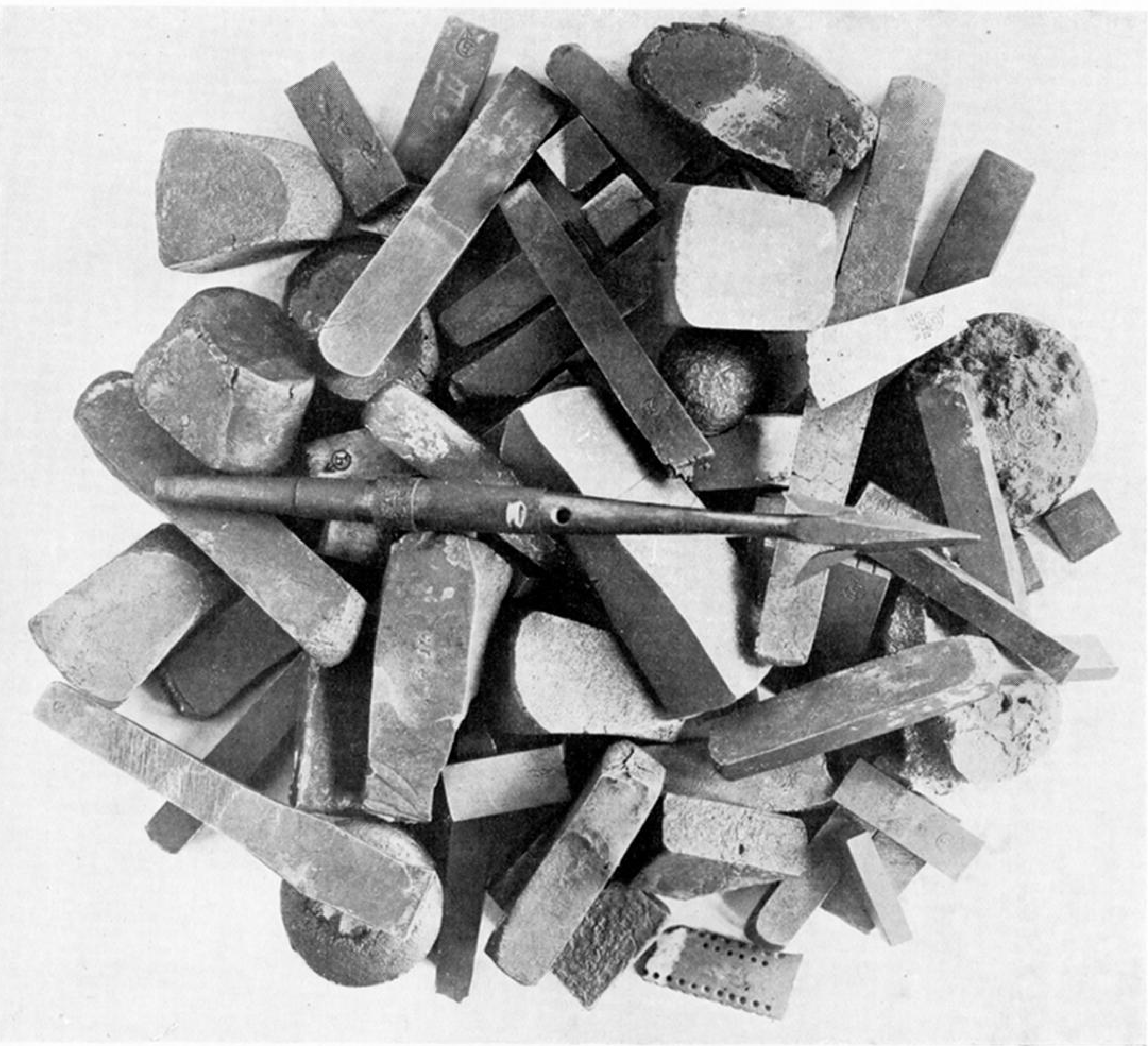
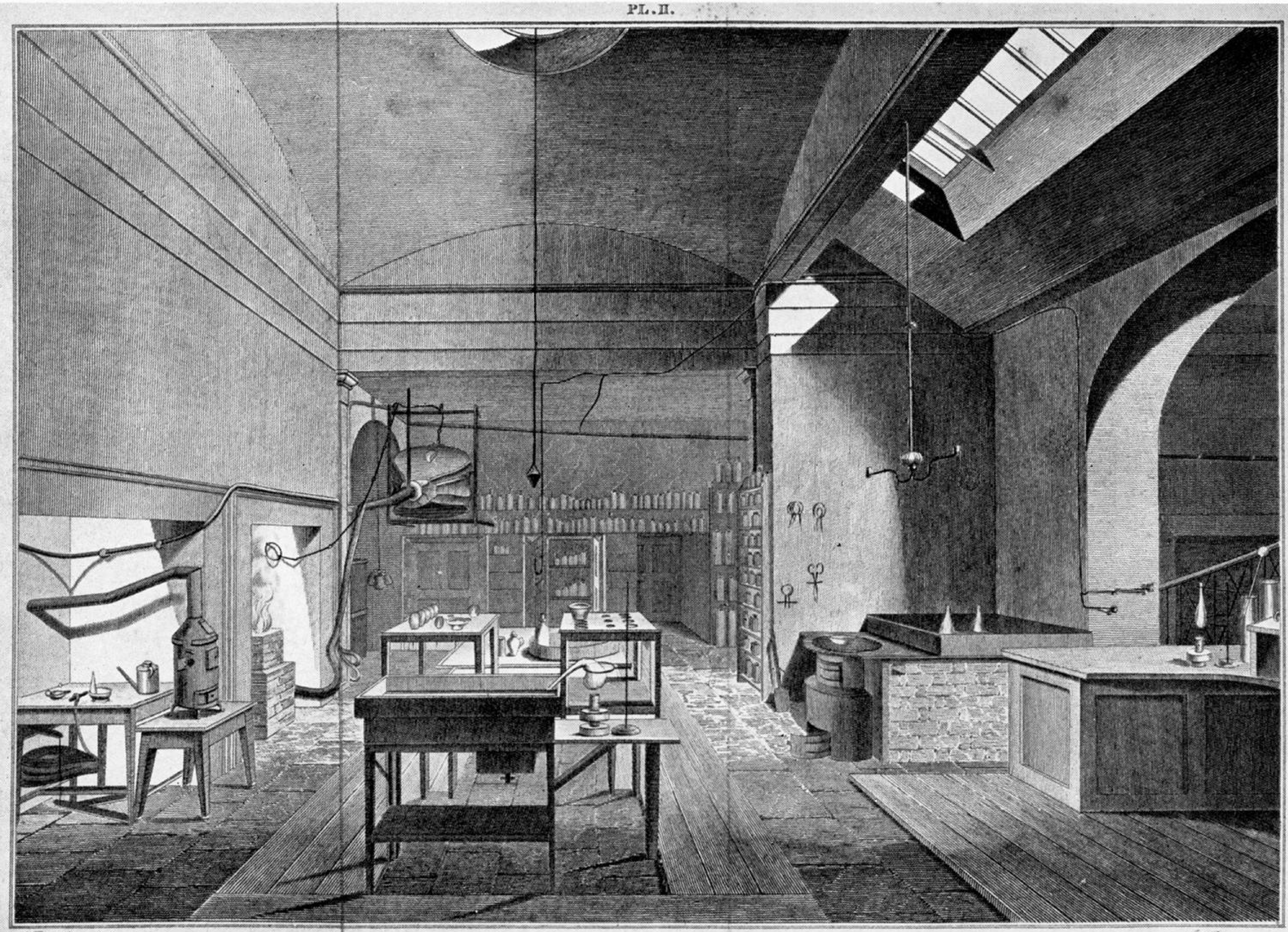


Fig. 2.—The 79 steel specimens taken from the box shown in fig. 1.

PL. II.



Interior View of the Laboratory in the Royal Institution.

Fig. 4.—The Laboratory at the Royal Institution, as it was in Faraday's time: from Brande's "Manual of Chemistry," 1819.

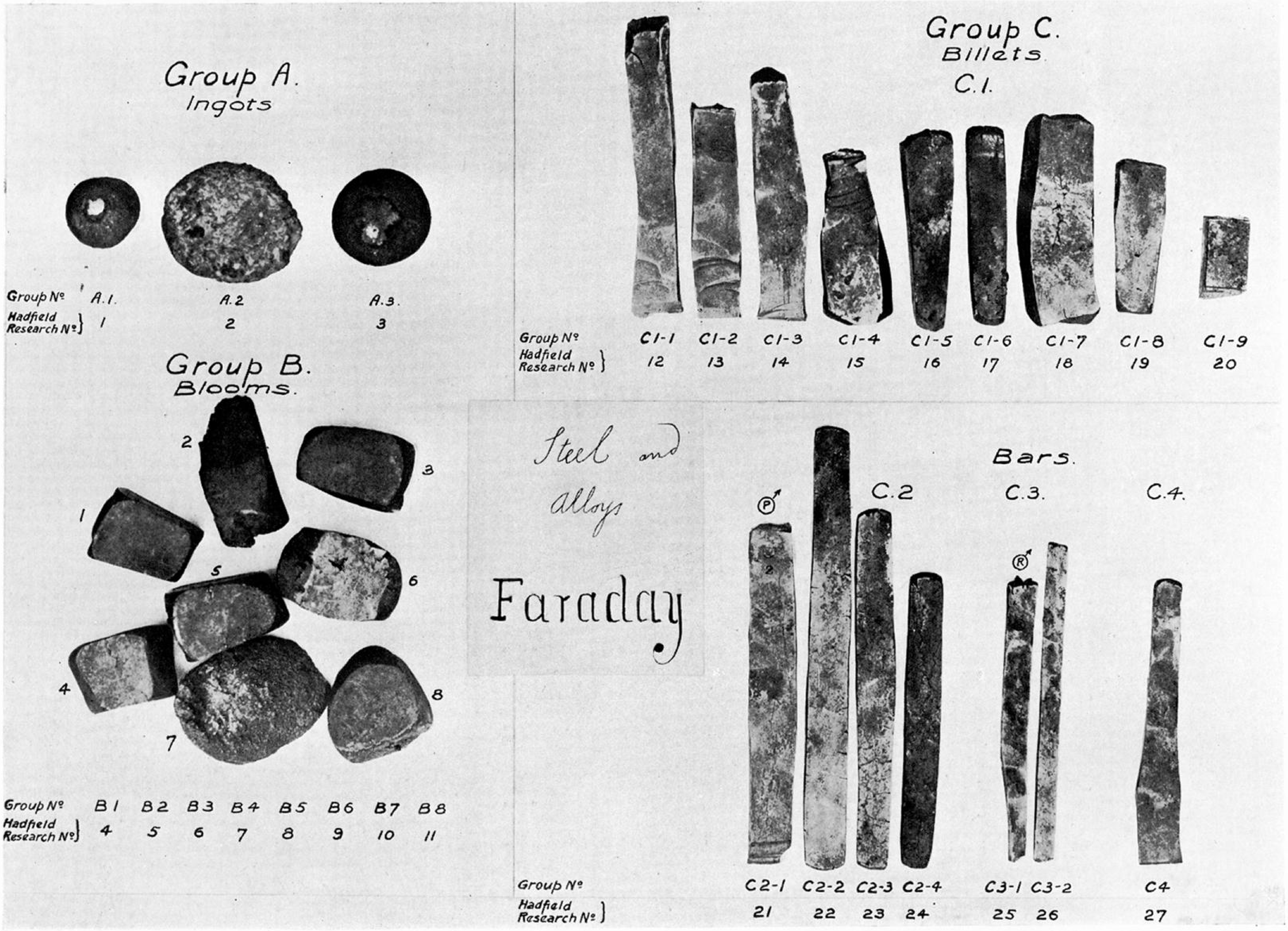

Group A.
Ingots
Group Nº A.1. A.2 A.3.
Hadfield Research Nº 1 2 3
Group B.
Blooms.
1
2
3
4
5
6
7
8
Group Nº B1 B2 B3 B4 B5 B6 B7 B8
Hadfield Research Nº 4 5 6 7 8 9 10 11
Group C.
Billets
C.1.
Group Nº C1-1 C1-2 C1-3 C1-4 C1-5 C1-6 C1-7 C1-8 C1-9
Hadfield Research Nº 12 13 14 15 16 17 18 19 20
Steel and Alloys
Faraday
Bars.
C.2
C.3.
C.4.
Ⓟ
Ⓡ
Group Nº C2-1 C2-2 C2-3 C2-4 C3-1 C3-2 C4
Hadfield Research Nº 21 22 23 24 25 26 27

Fig. 5.

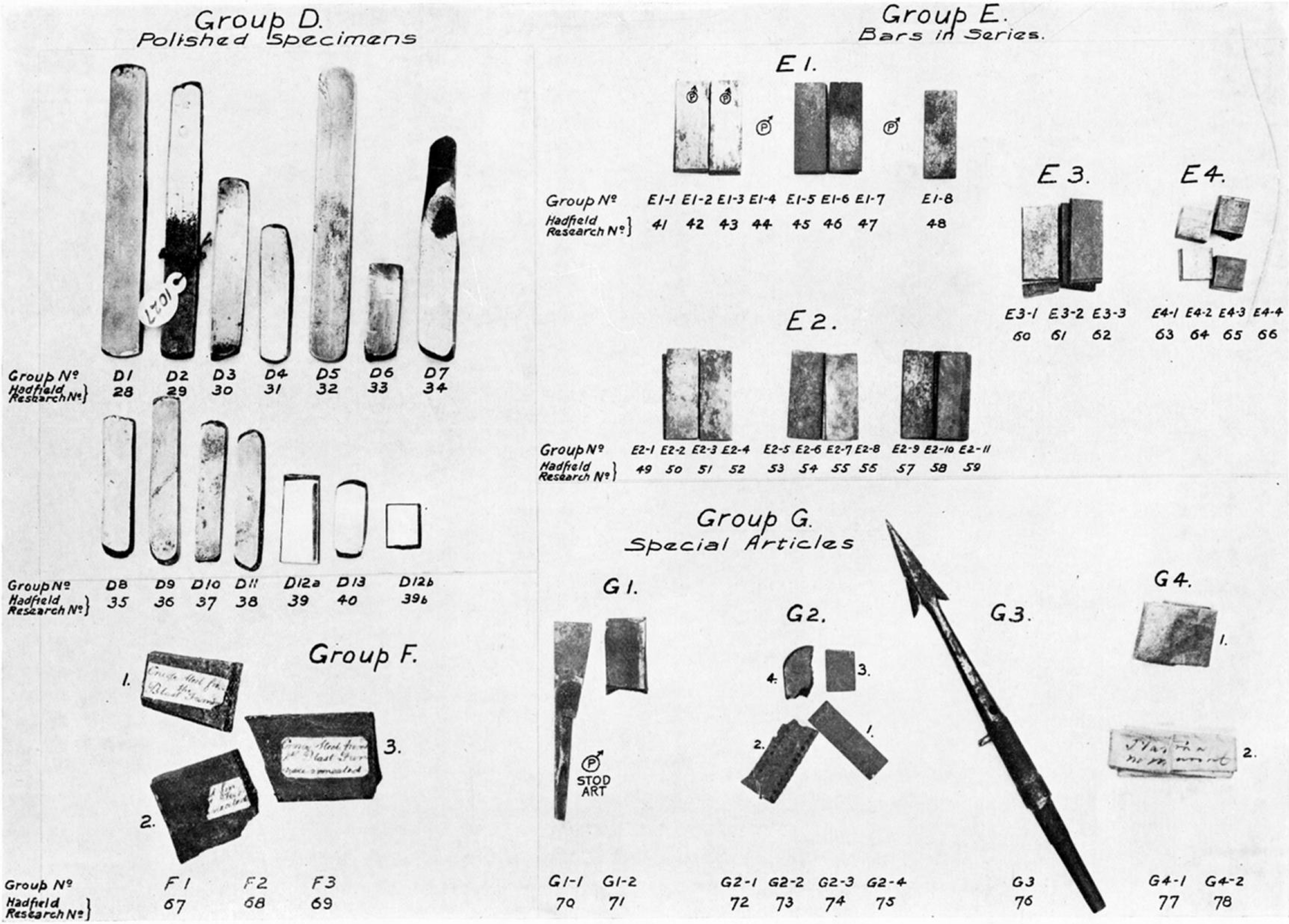
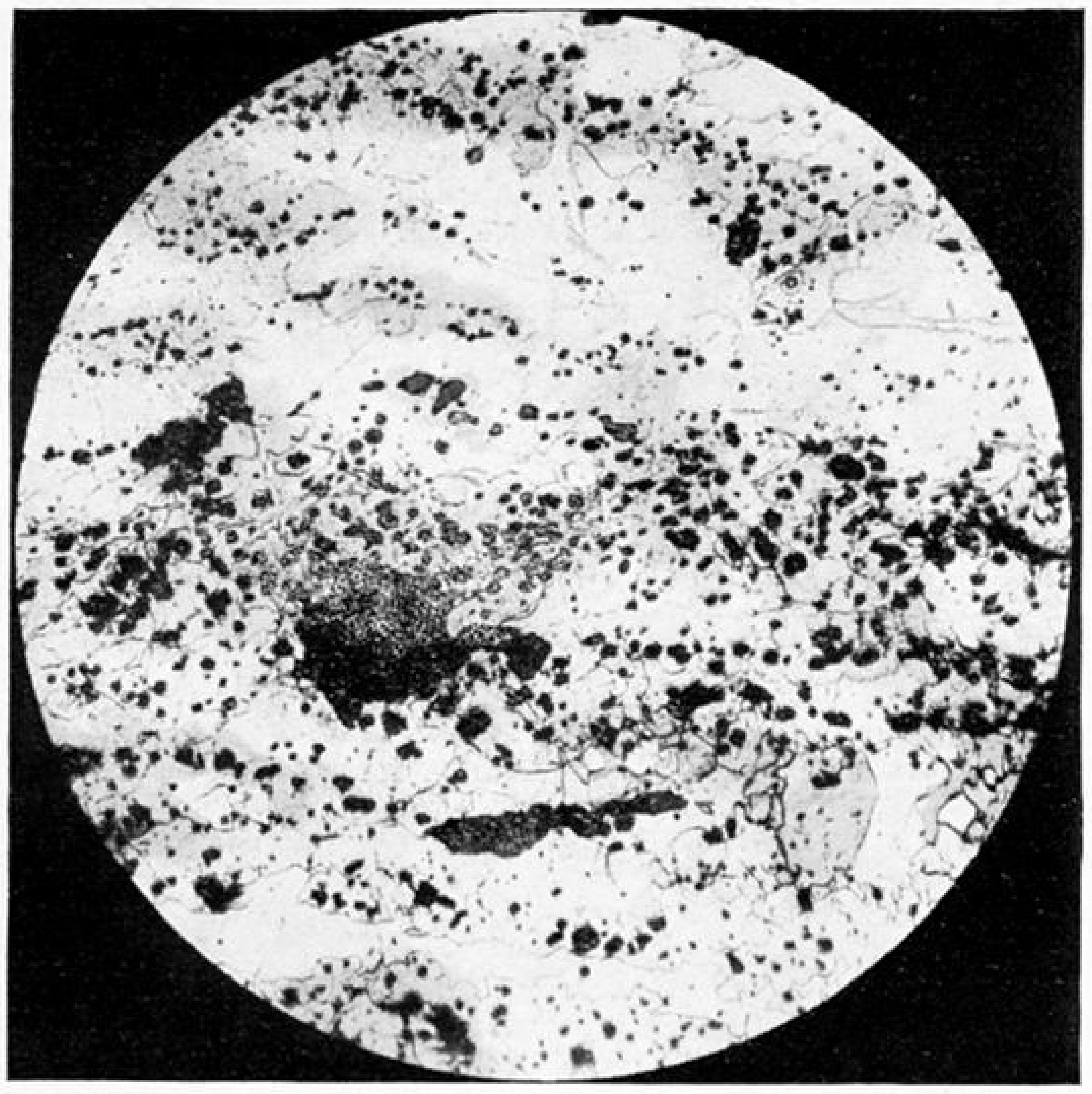

Group D.
Polished Specimens
1027
Group Nº D1 D2 D3 D4 D5 D6 D7
Hadfield Research Nº 28 29 30 31 32 33 34
Group Nº D8 D9 D10 D11 D12a D13 D12b
Hadfield Research Nº 35 36 37 38 39 40 39b
Group E.
Bars in Series.
E1.
Group Nº E1-1 E1-2 E1-3 E1-4 E1-5 E1-6 E1-7 E1-8
Hadfield Research Nº 41 42 43 44 45 46 47 48
E3.
E4.
E3-1 E3-2 E3-3
60 61 62
E4-1 E4-2 E4-3 E4-4
63 64 65 66
E2.
Group Nº E2-1 E2-2 E2-3 E2-4 E2-5 E2-6 E2-7 E2-8 E2-9 E2-10 E2-11
Hadfield Research Nº 49 50 51 52 53 54 55 56 57 58 59
Group F.
1.
2.
3.
Group Nº F1 F2 F3
Hadfield Research Nº 67 68 69
Group G.
Special Articles
G1.
STOD ART
G2.
1.
2.
3.
4.
G3.
G4.
1.
2.
Group Nº G1-1 G1-2 G2-1 G2-2 G2-3 G2-4 G3 G4-1 G4-2
Hadfield Research Nº 70 71 72 73 74 75 76 77 78

Fig. 6.



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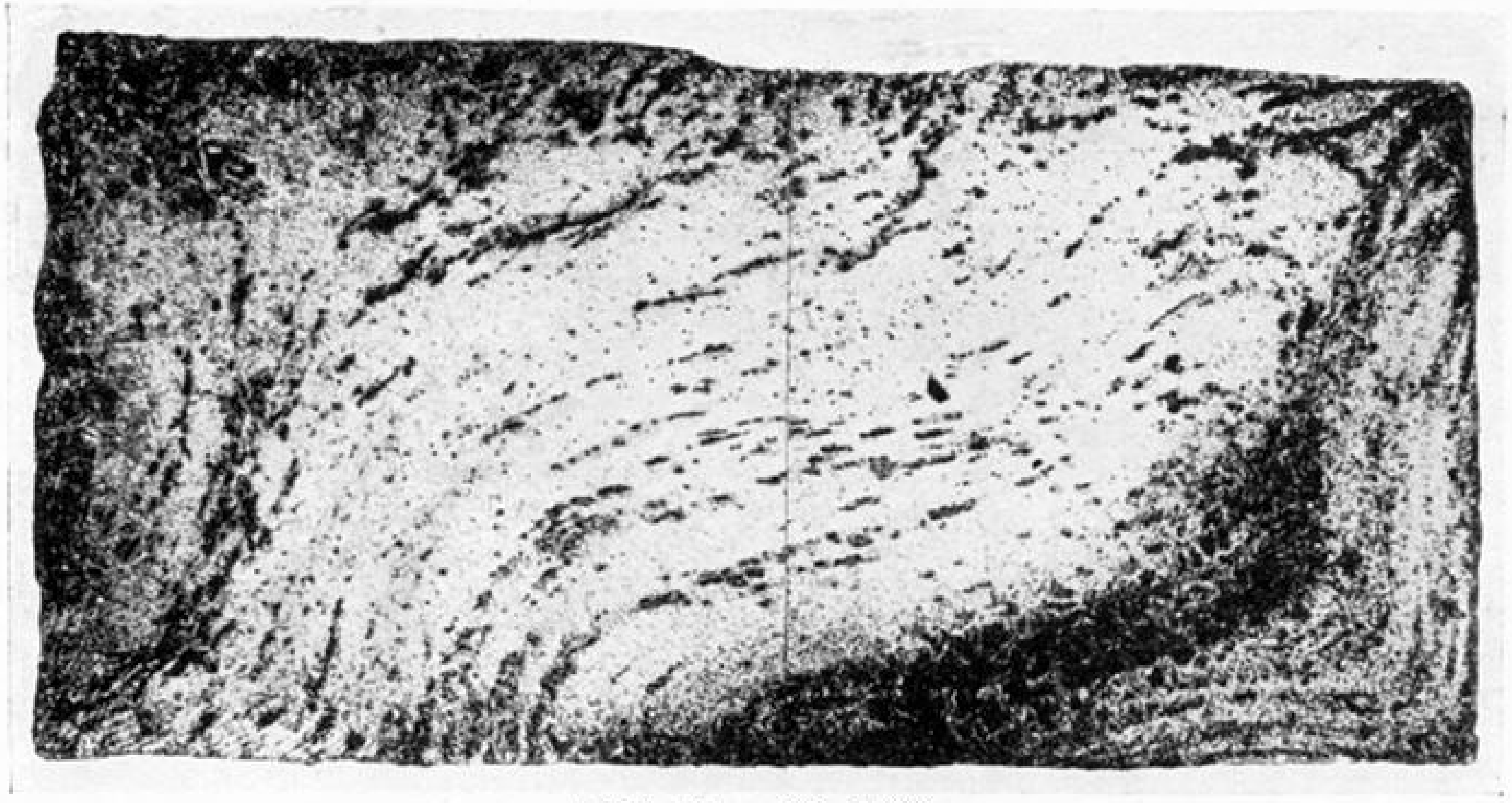
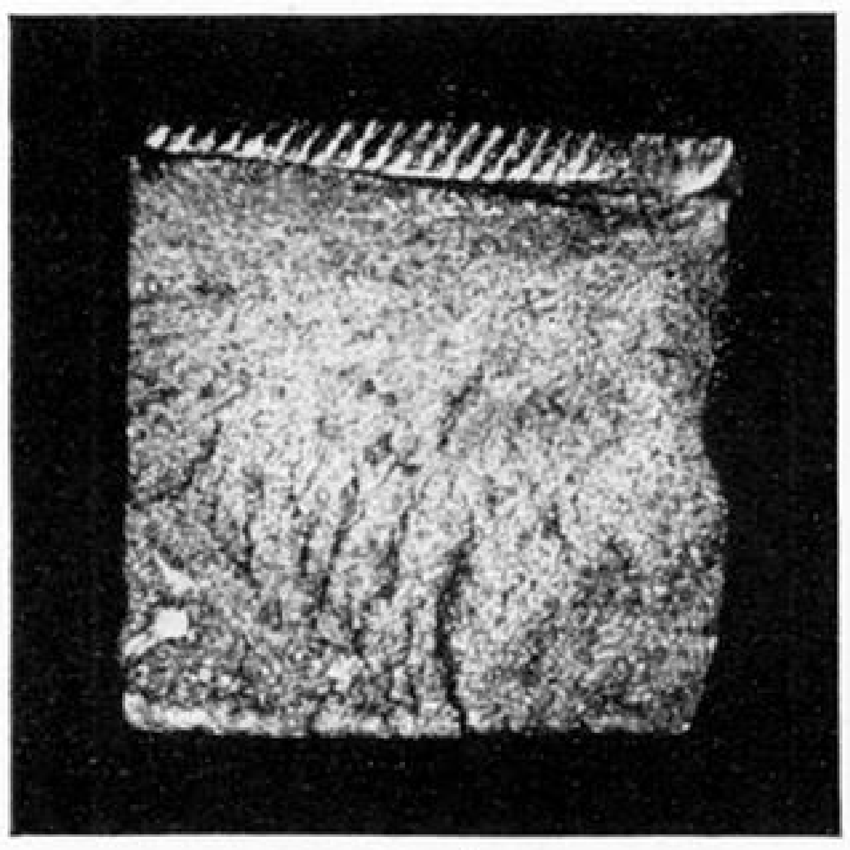


PM. 2. (X 12).



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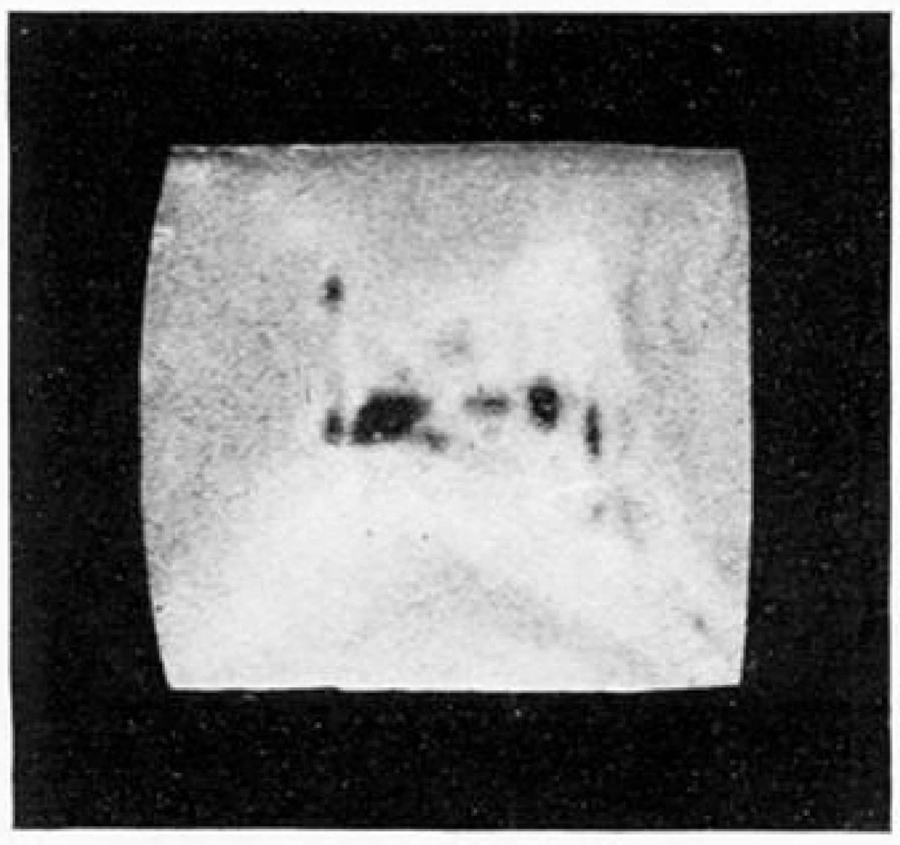

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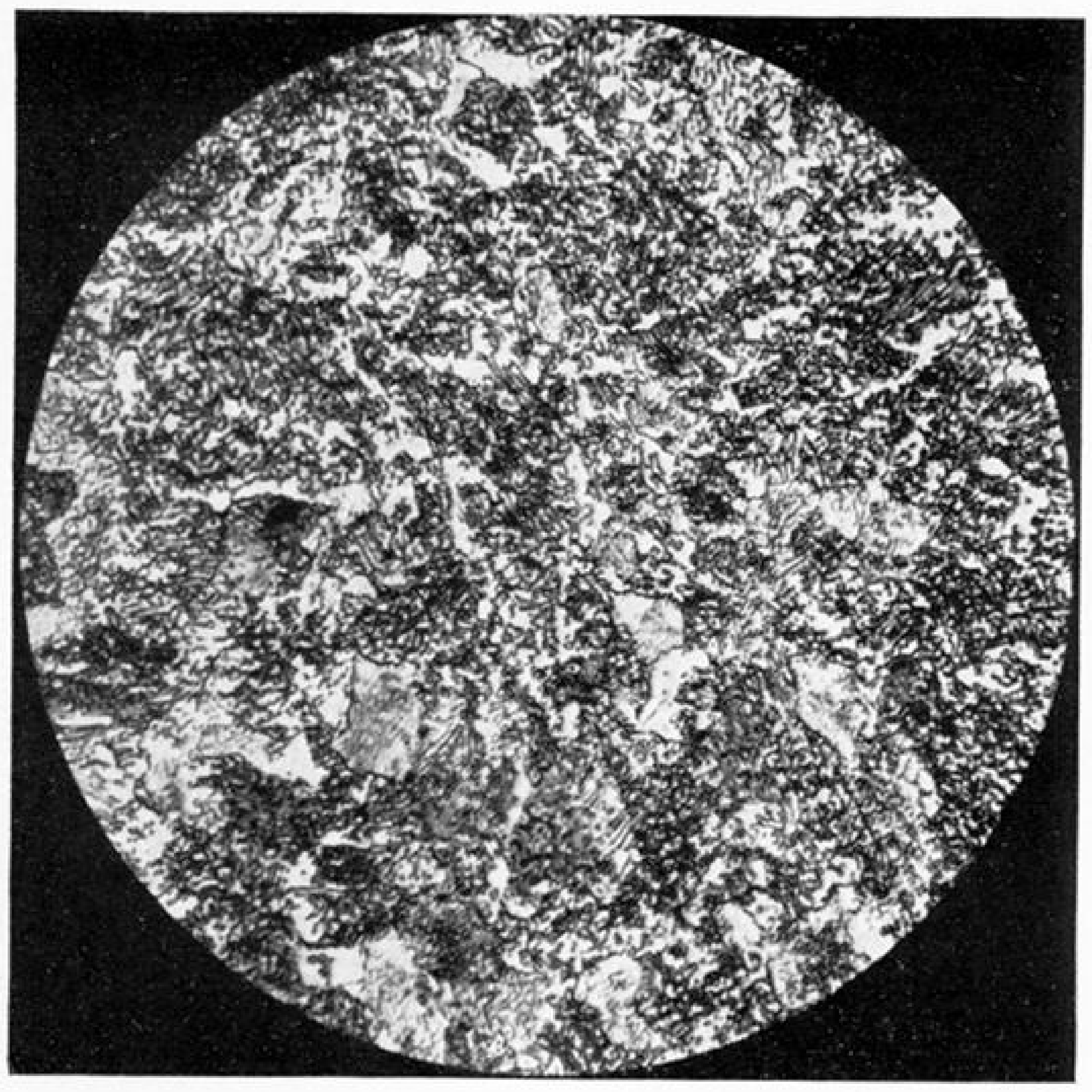

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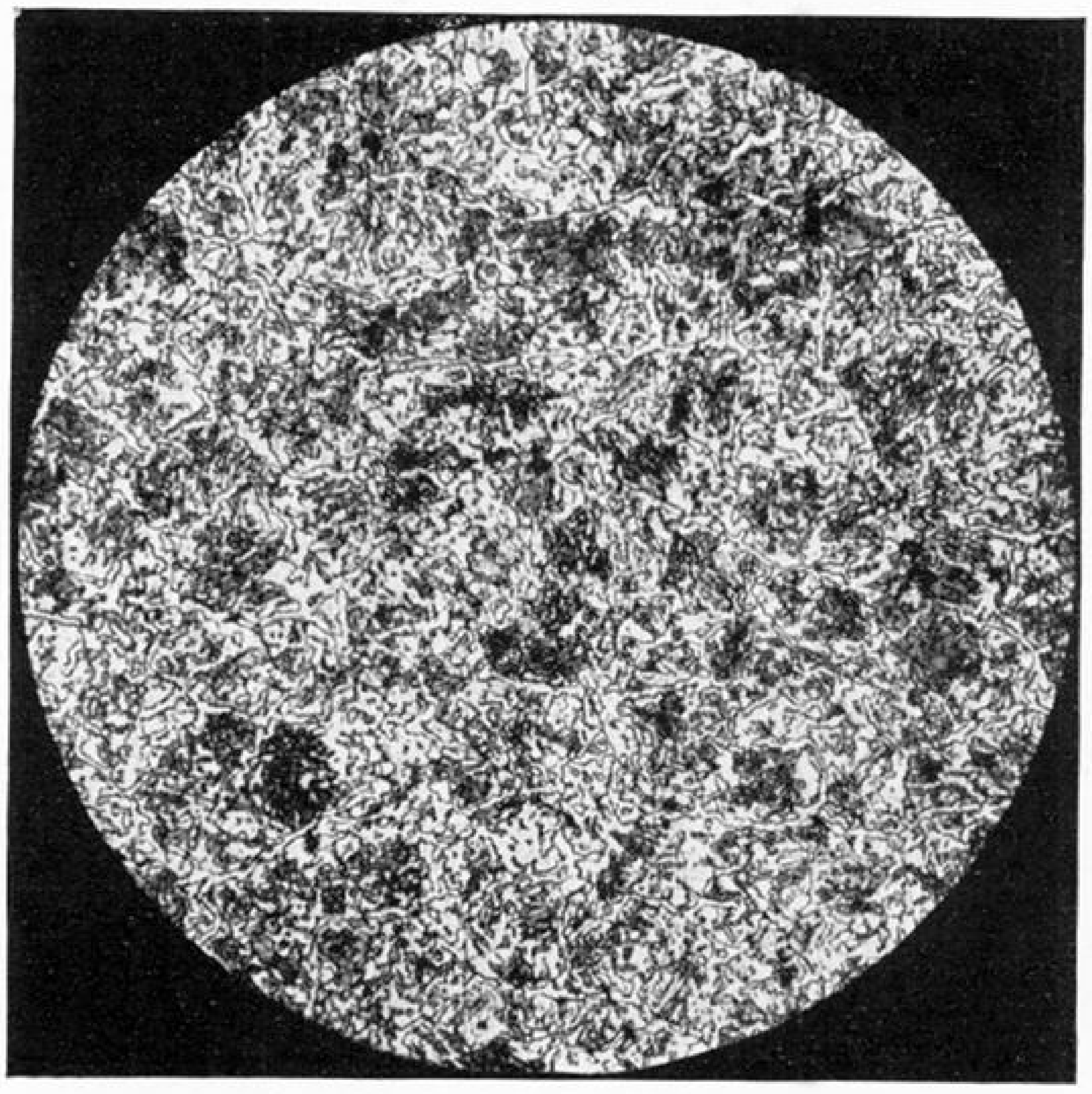
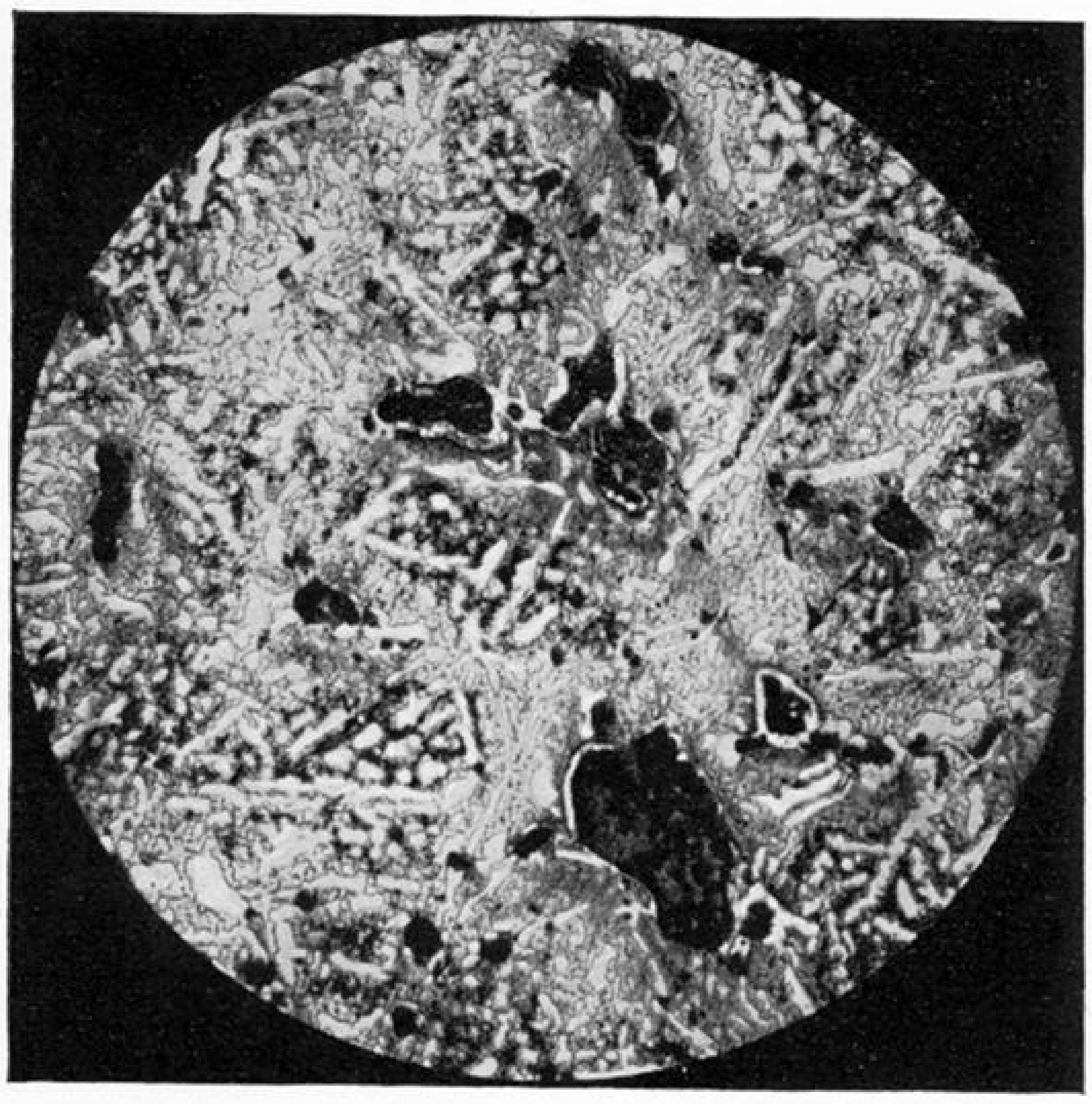
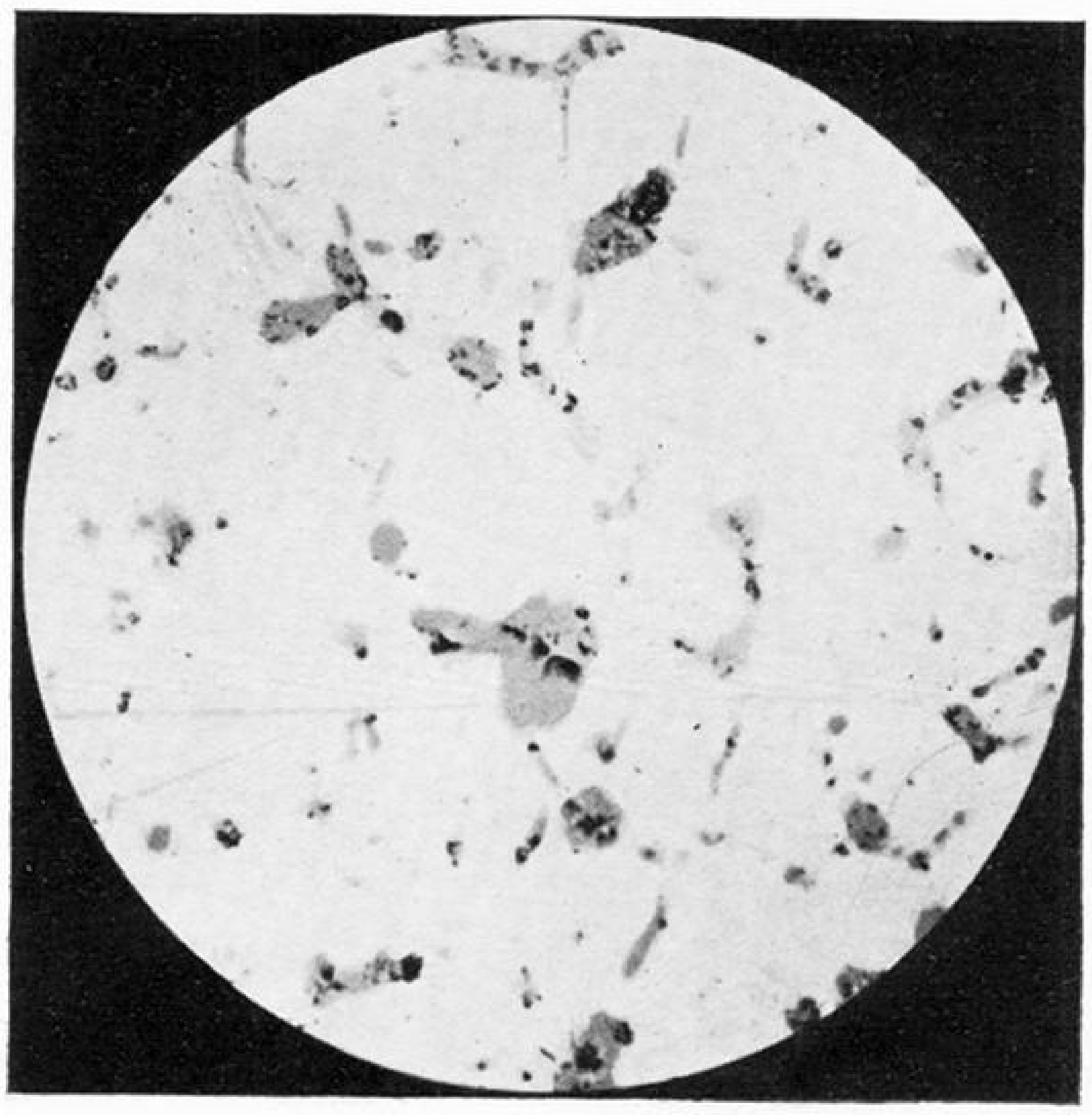


PM. 6. (X 400).



PM. 7. (X 200).



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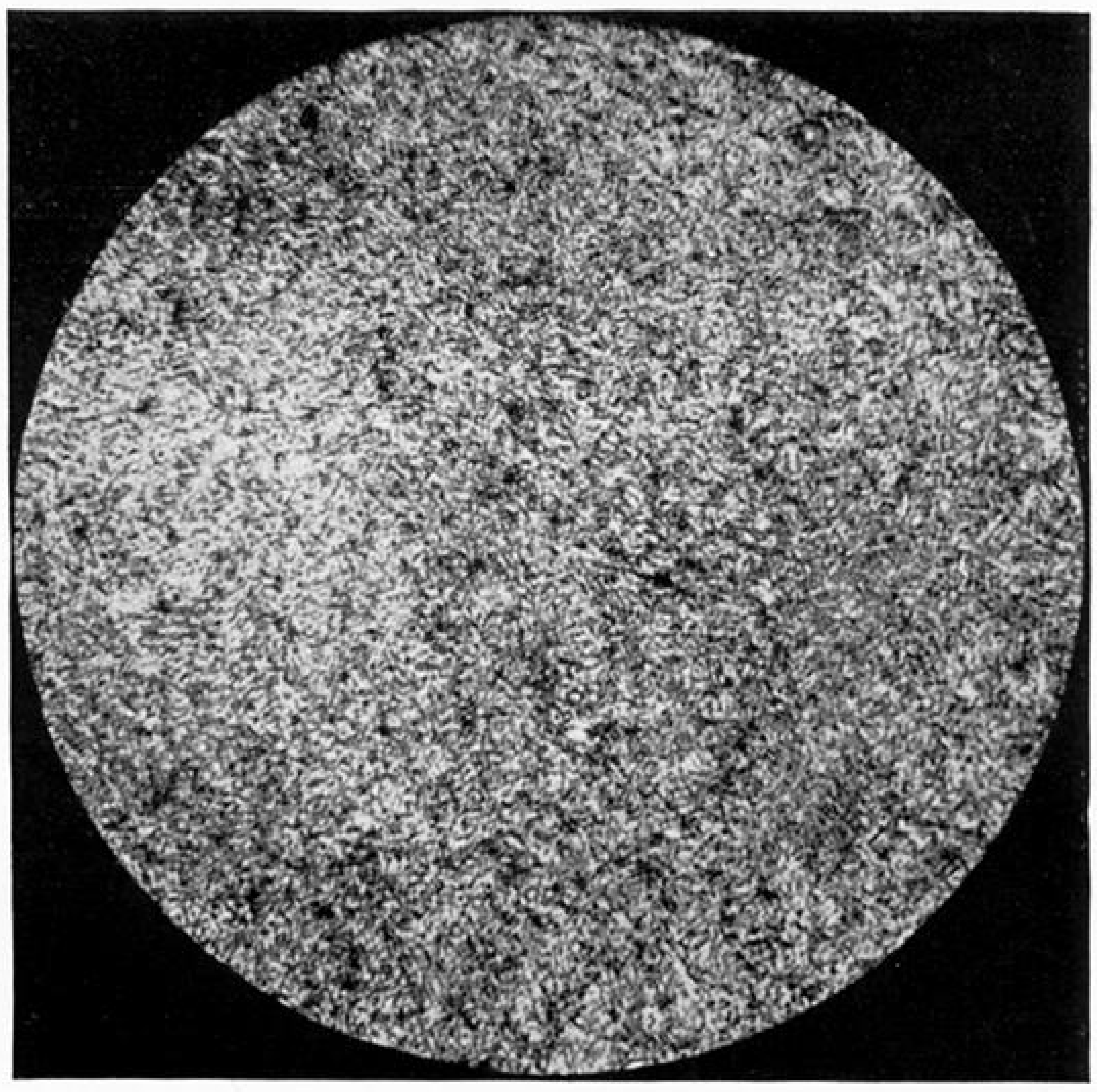

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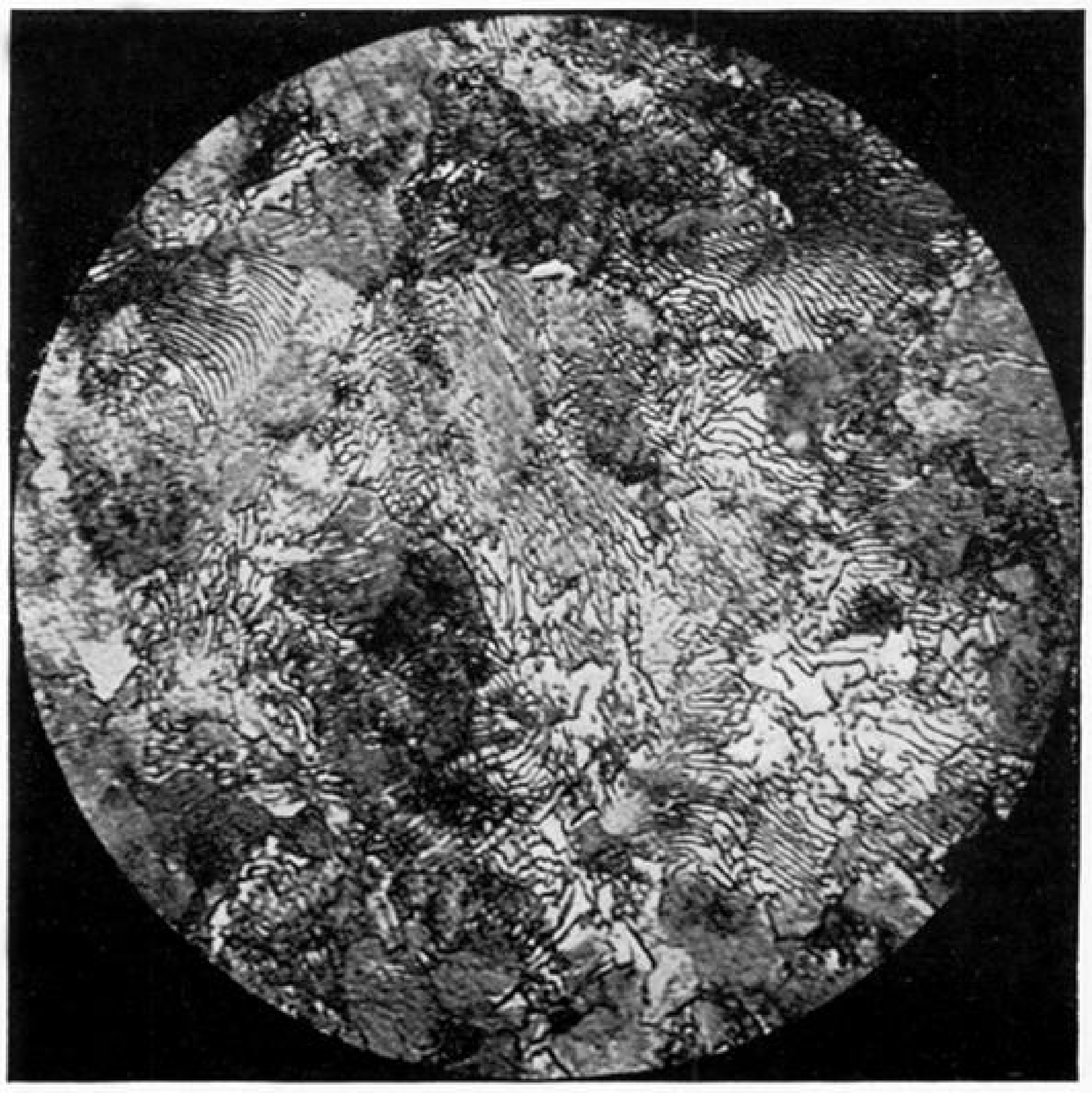

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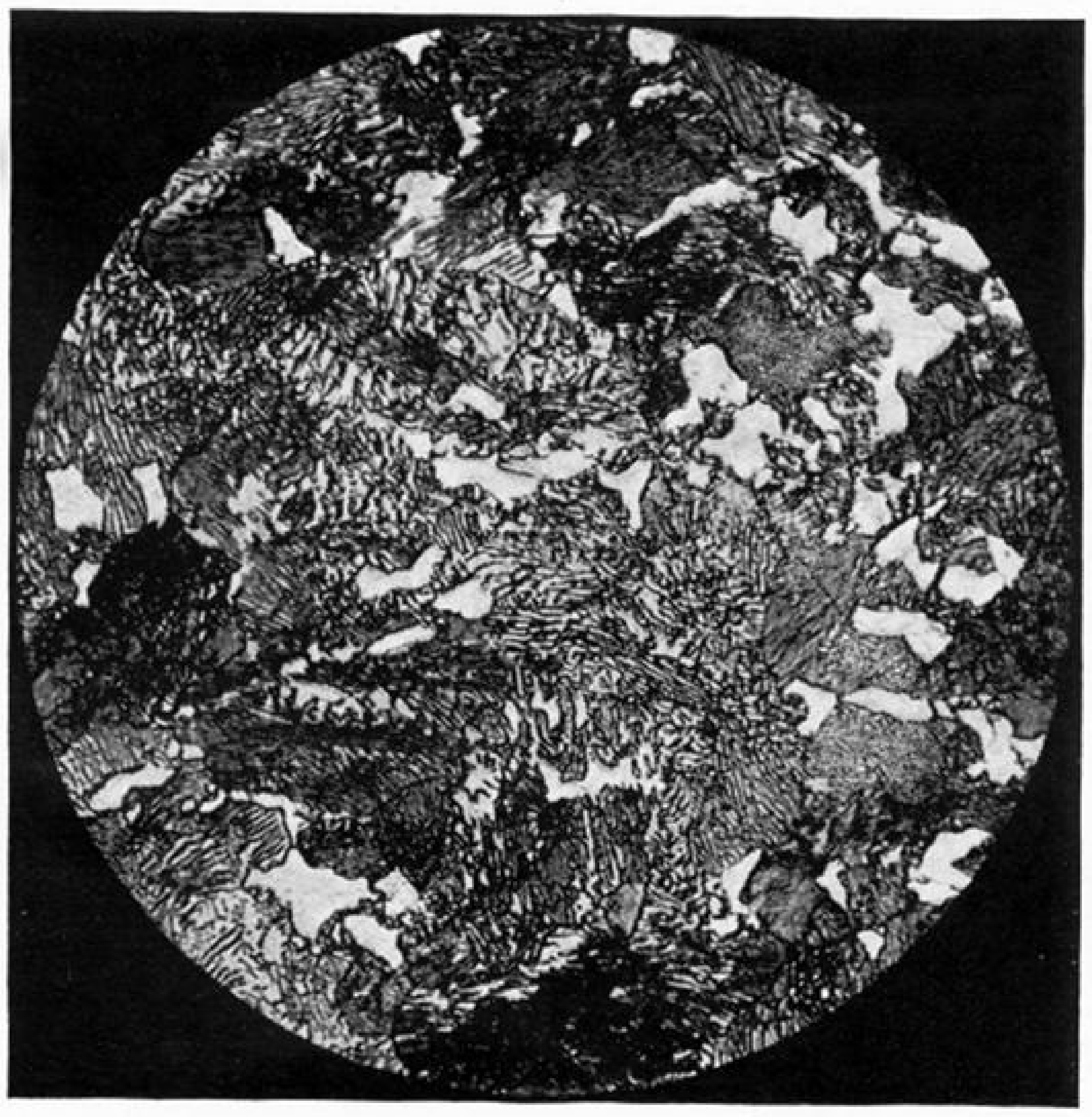

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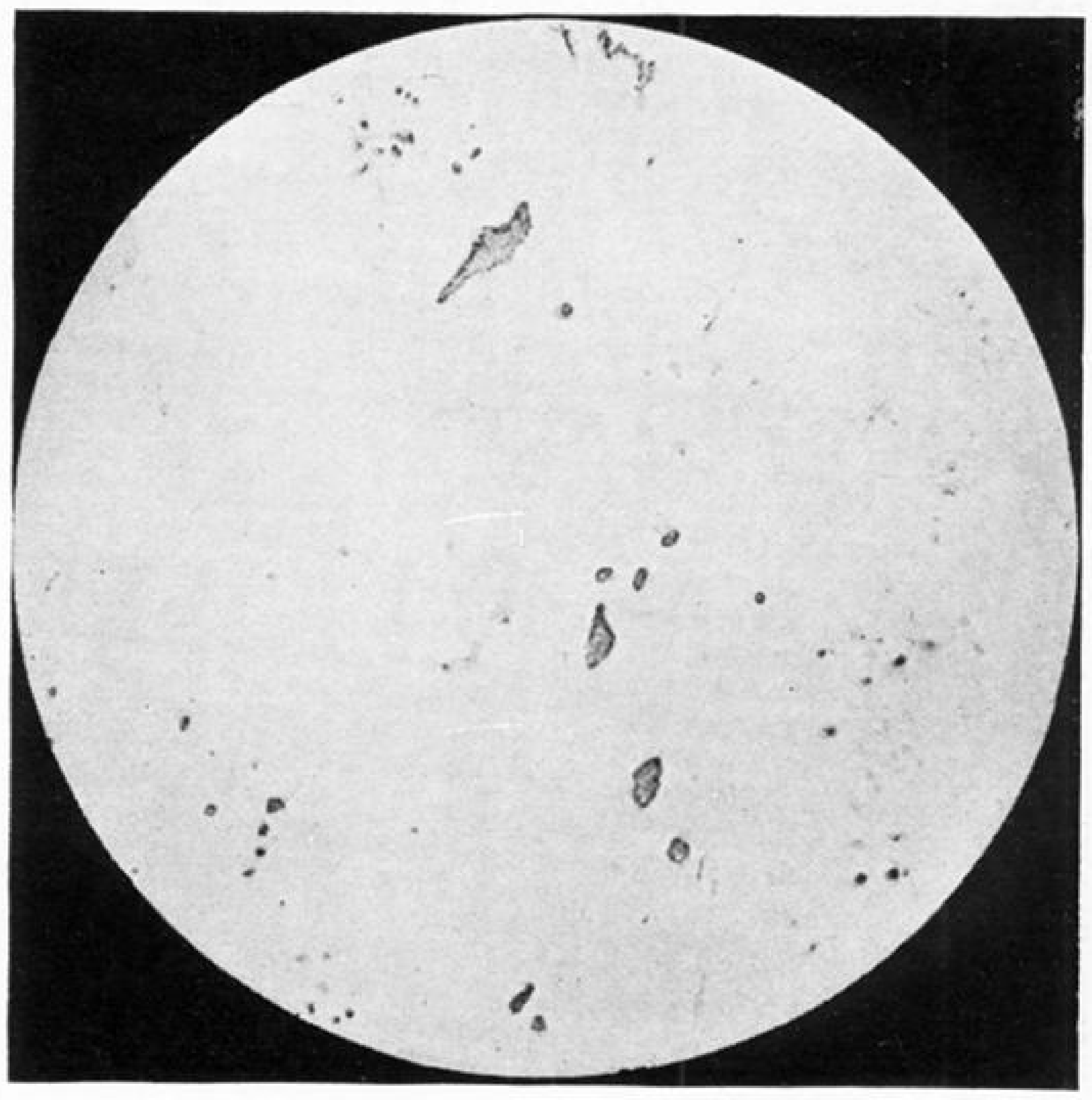

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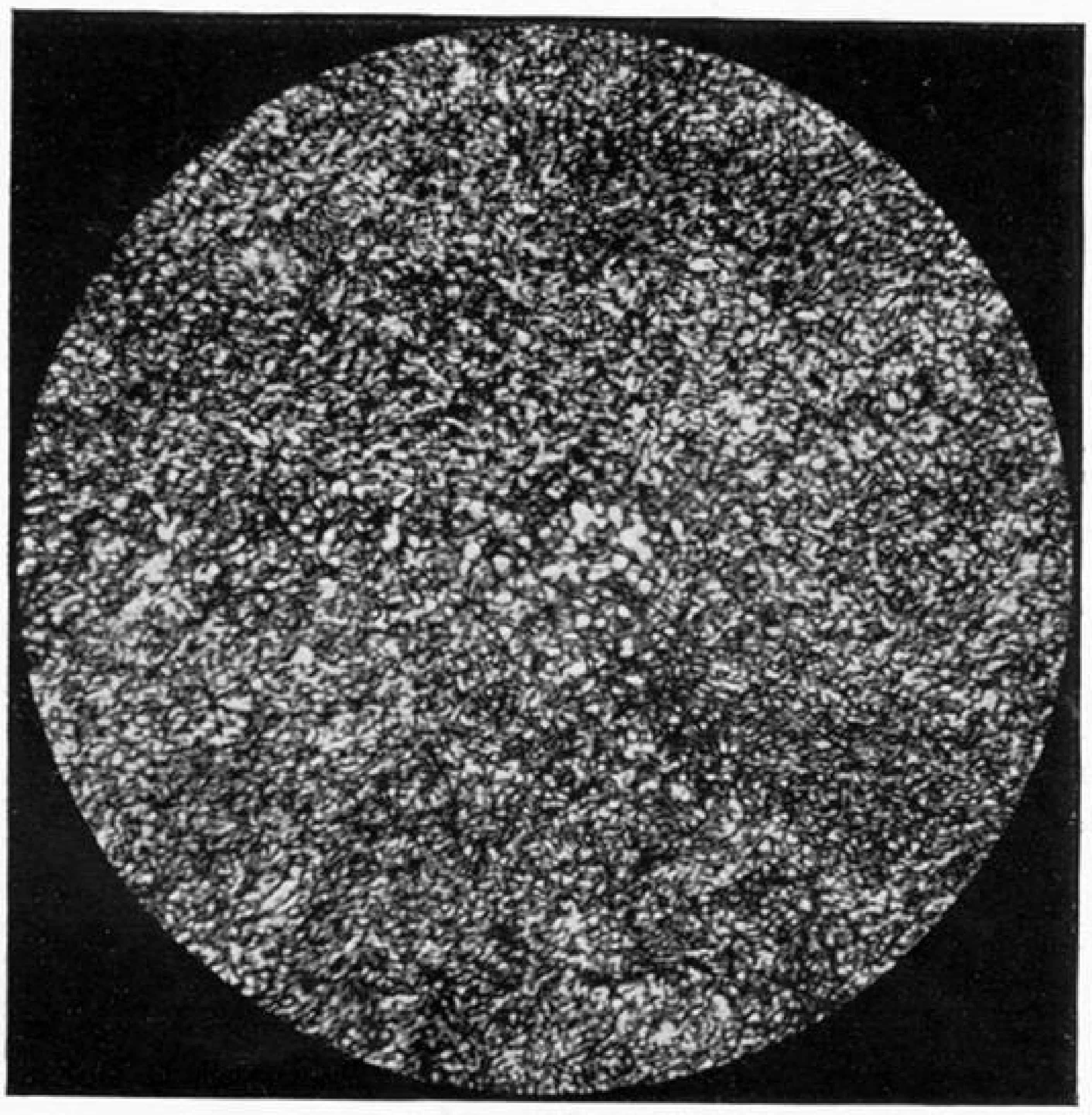

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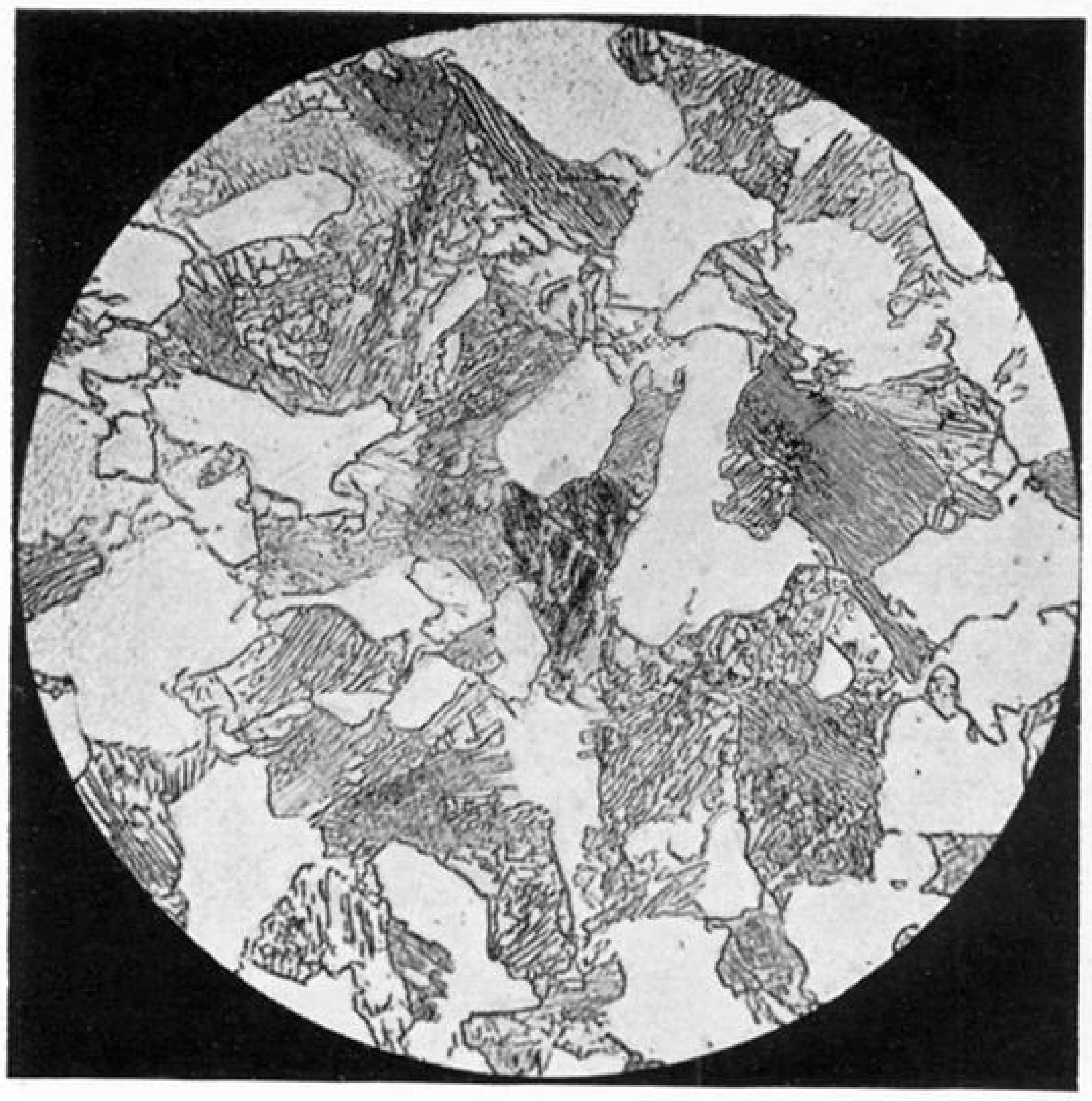

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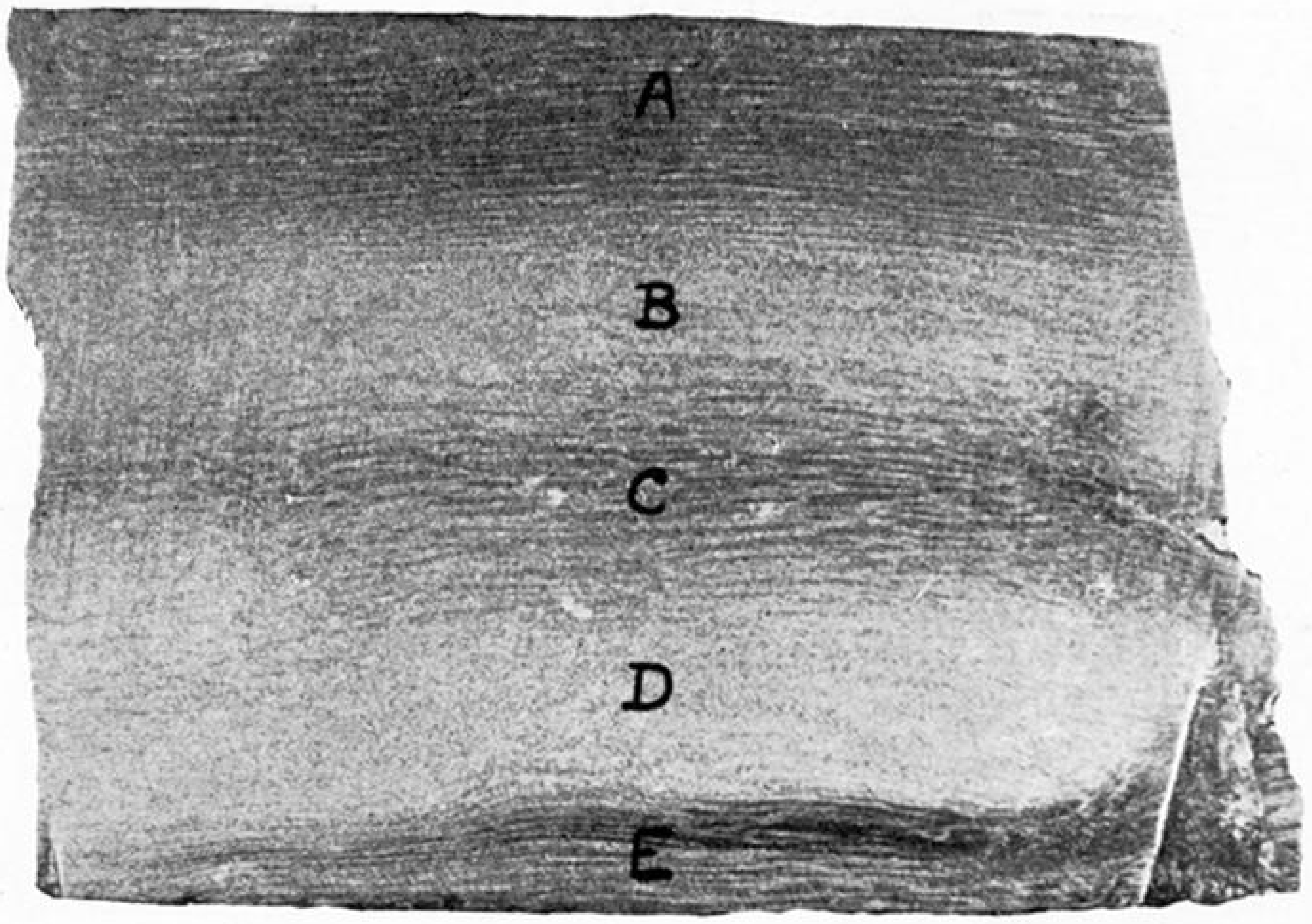

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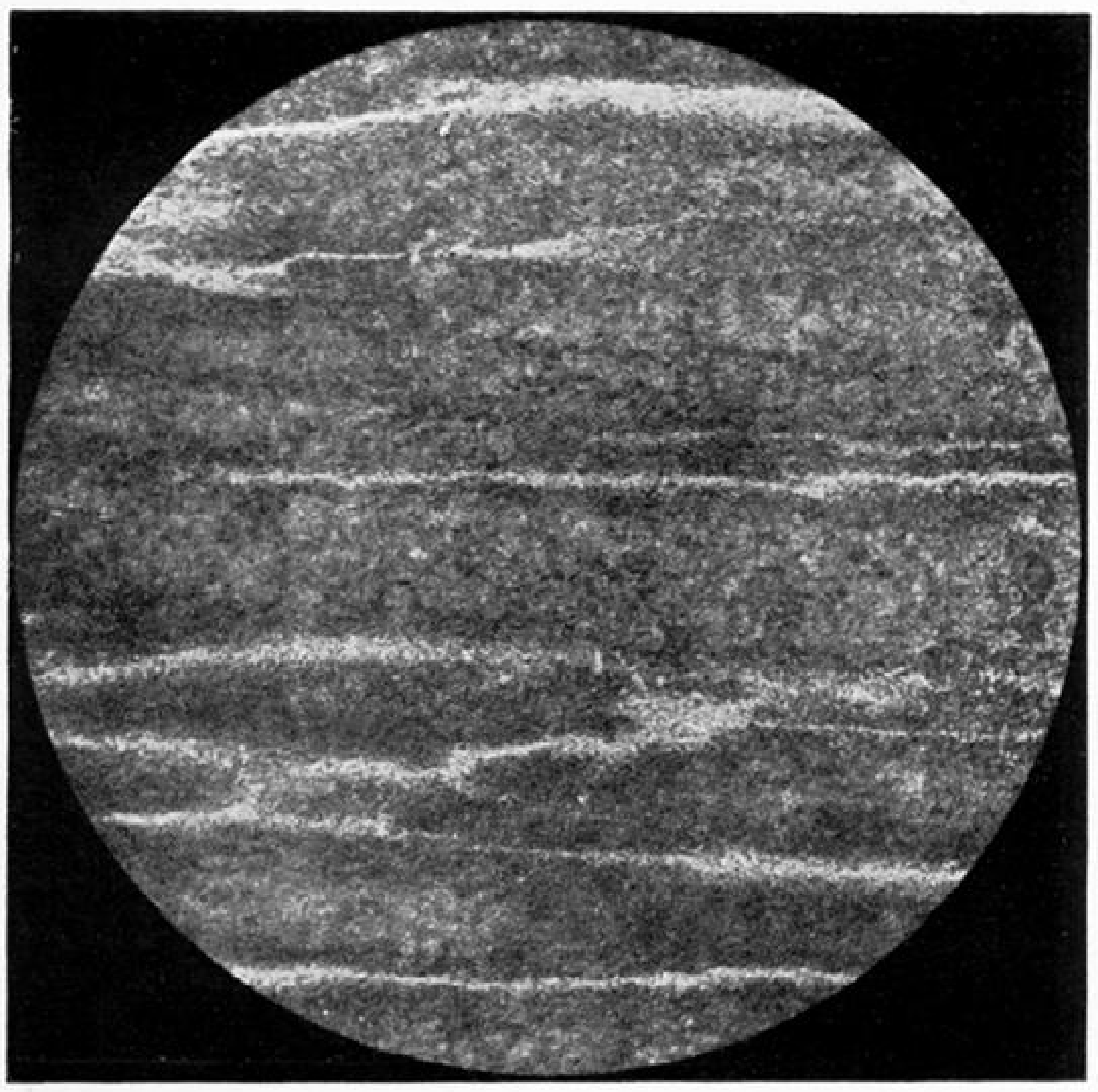

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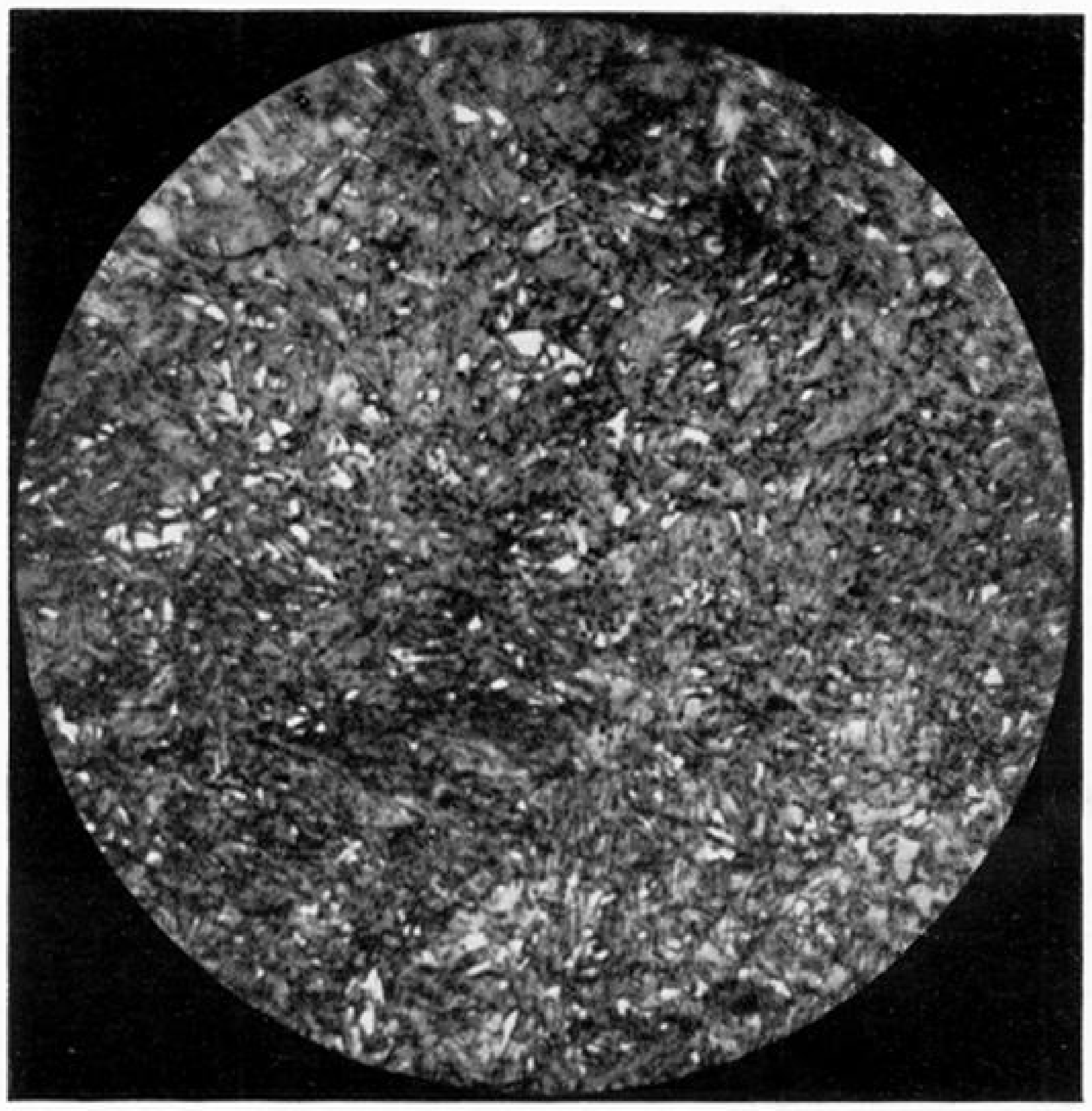

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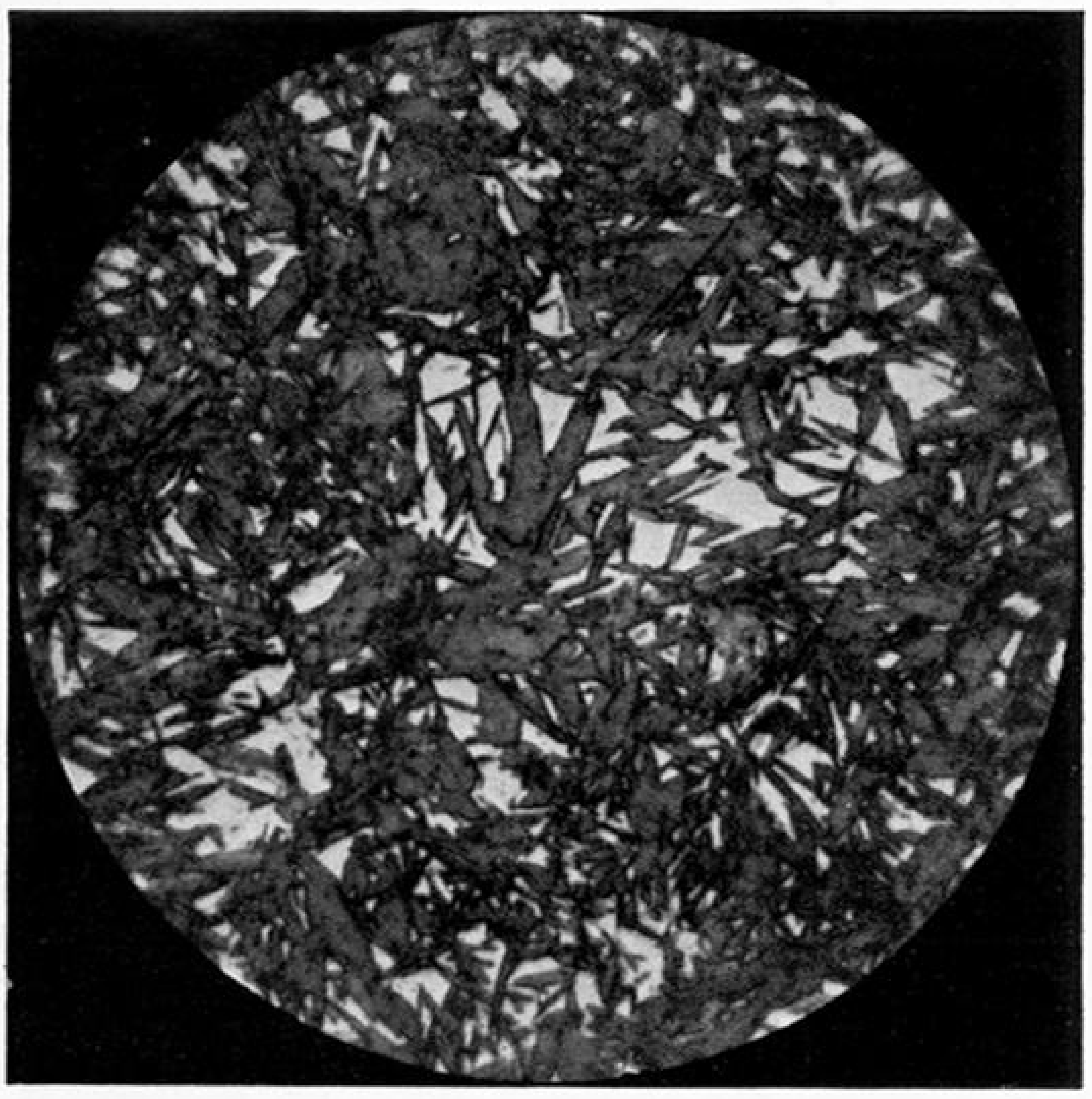

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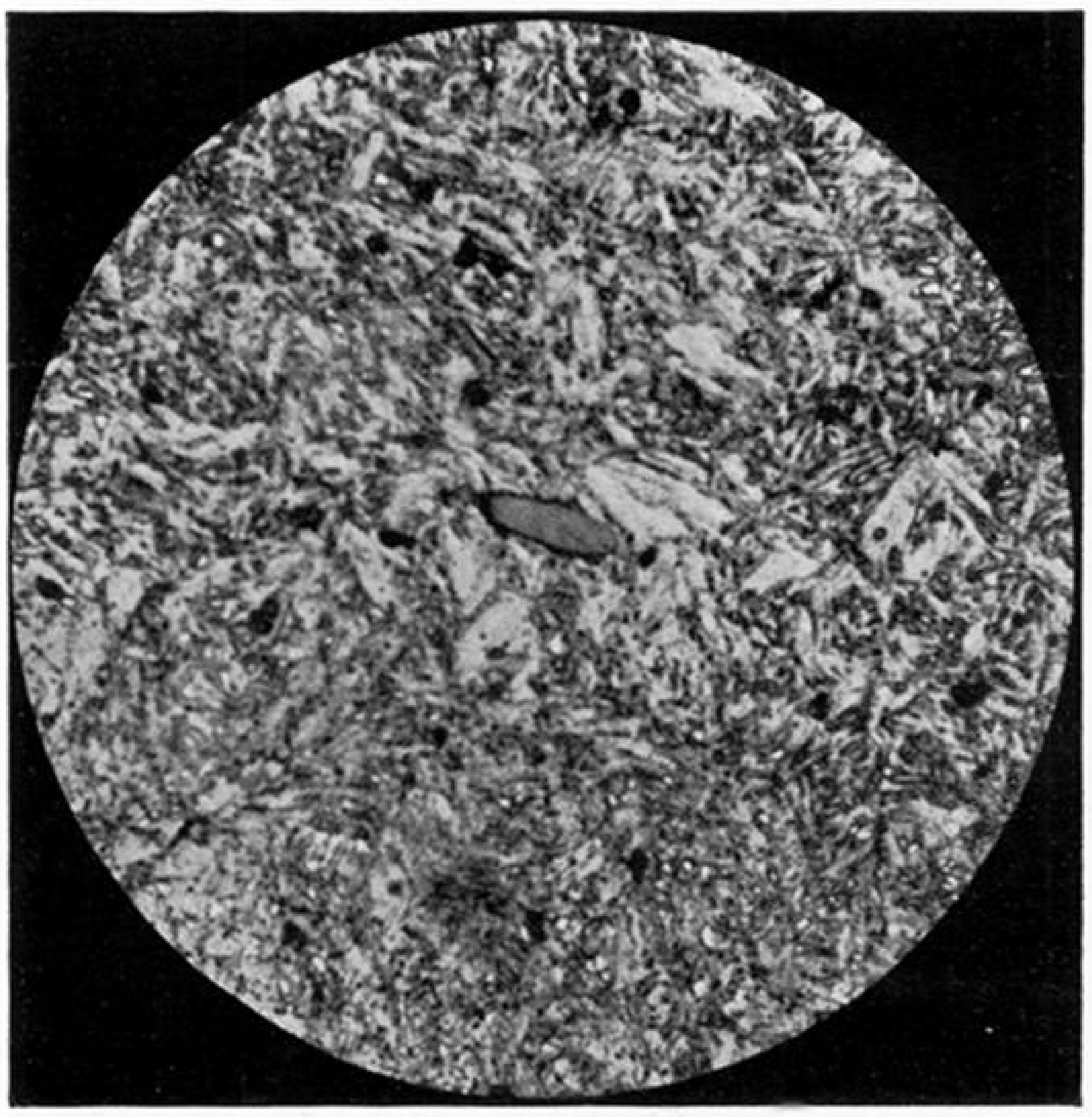

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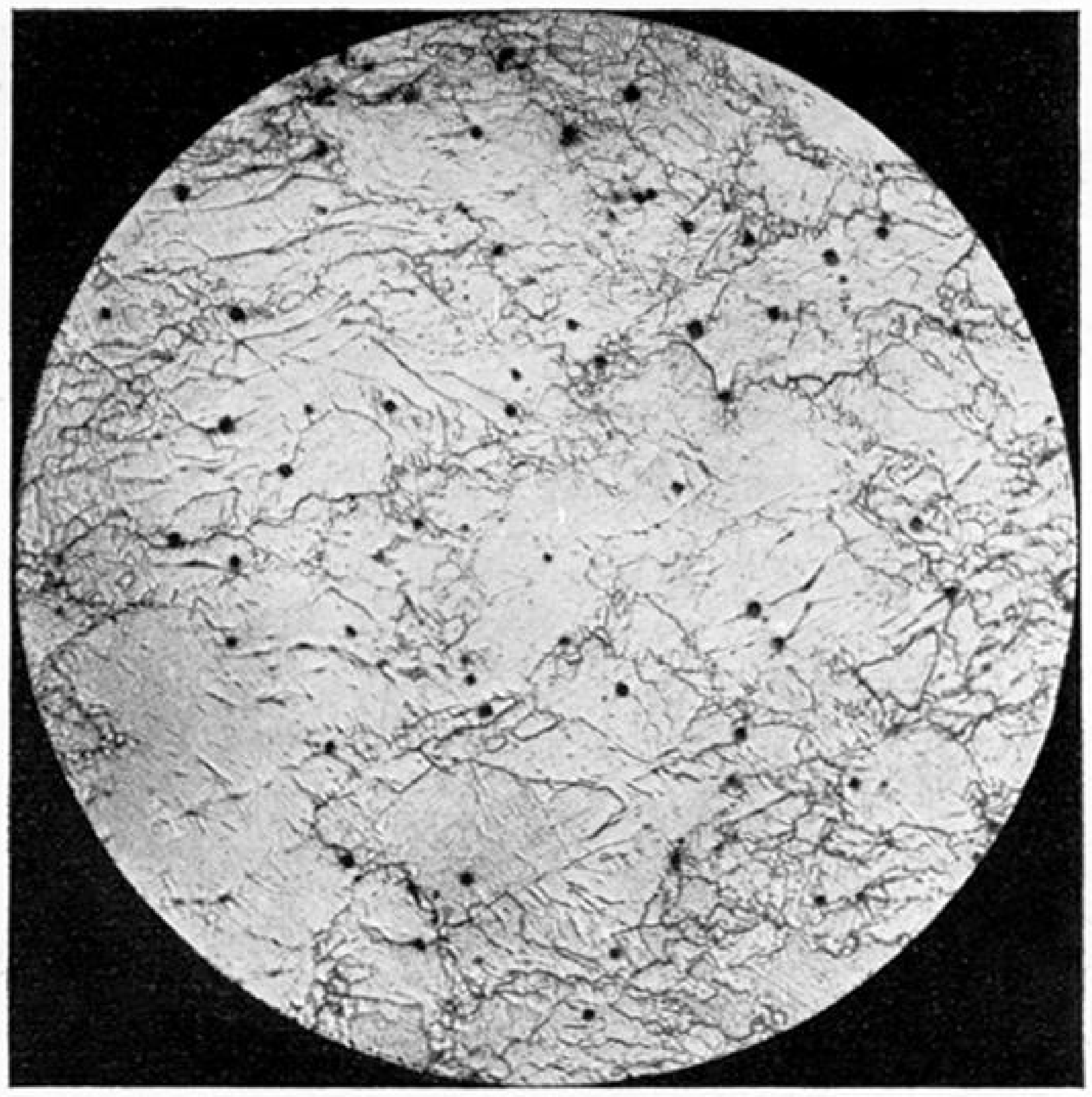

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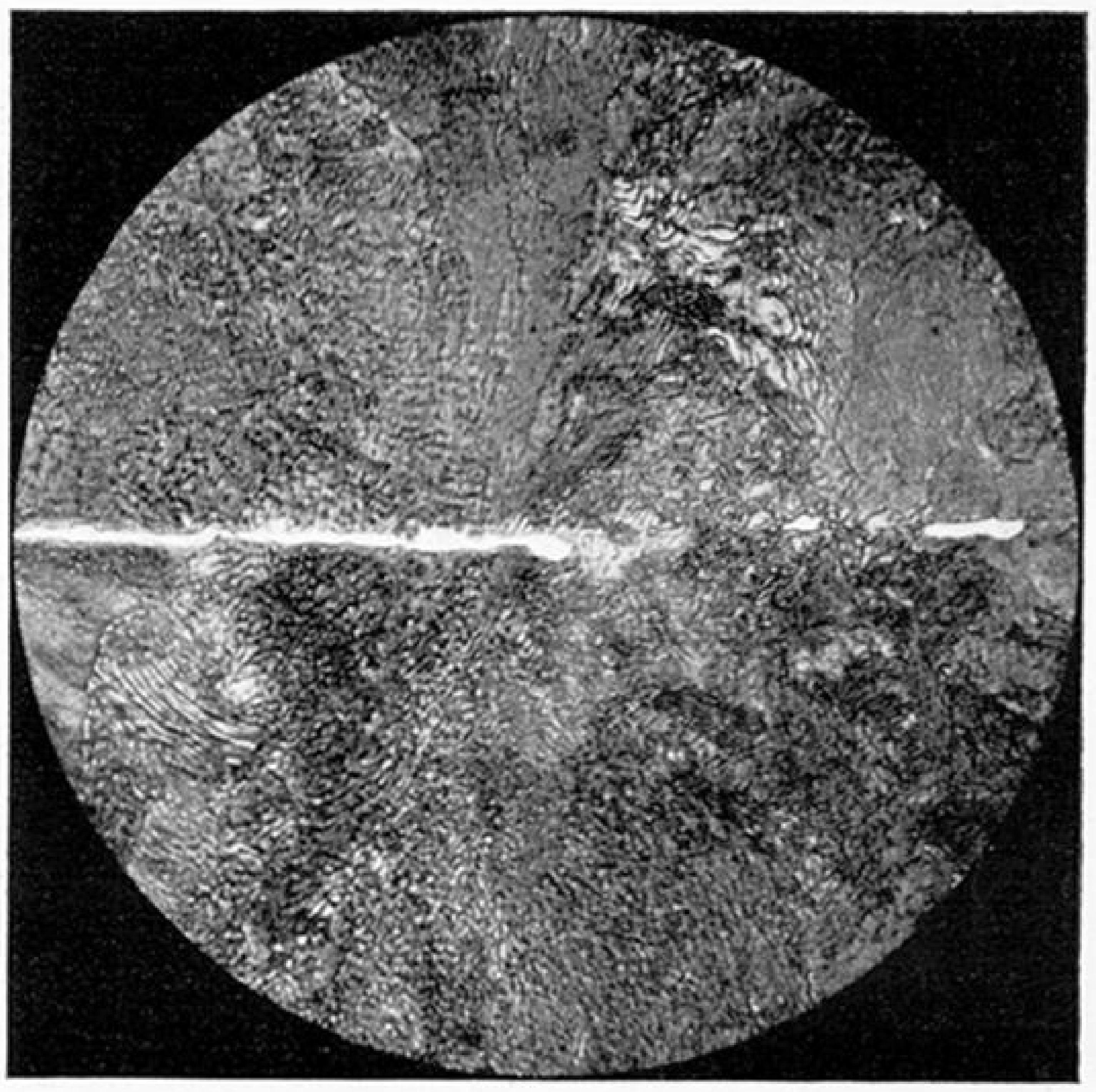

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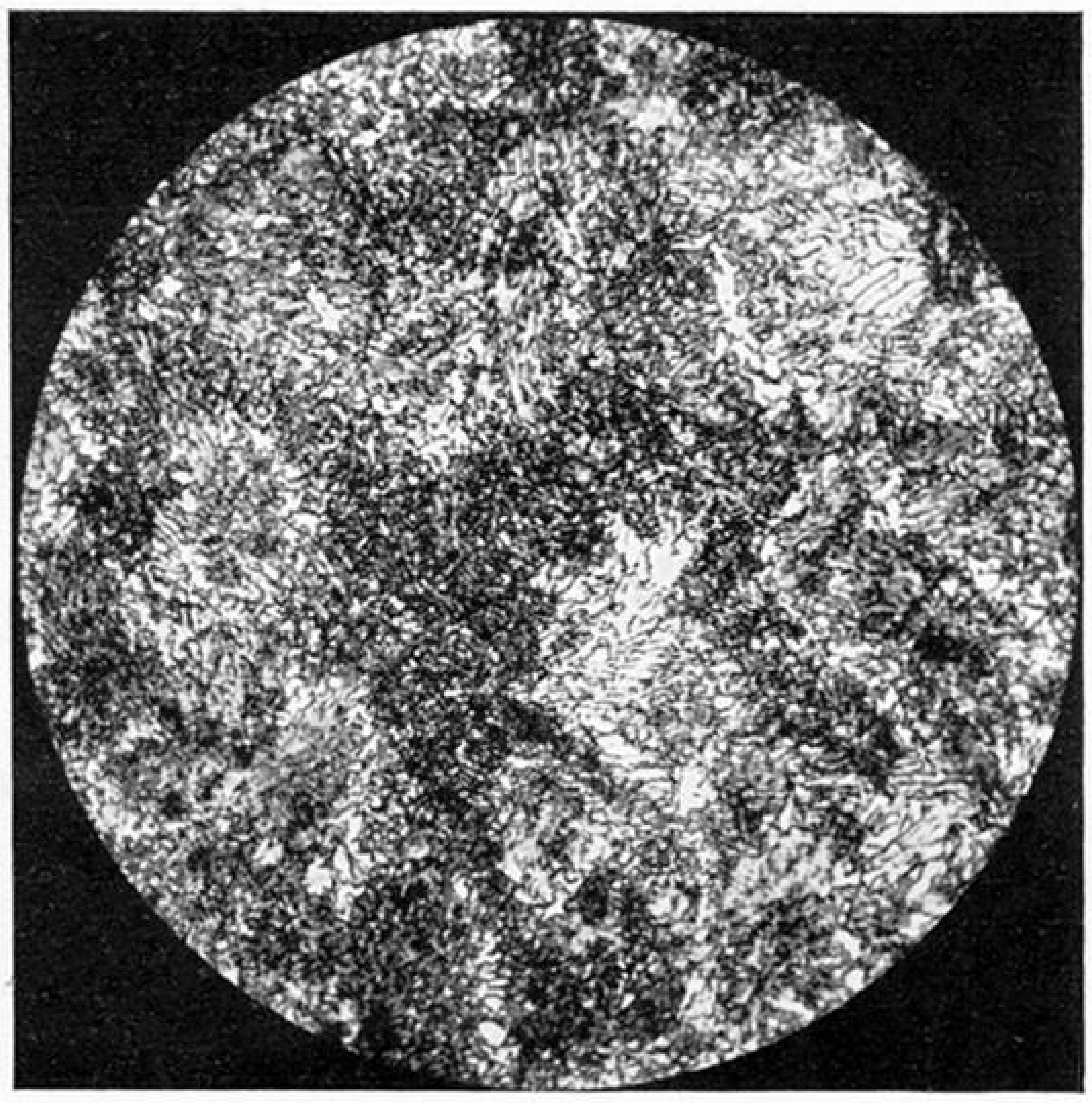

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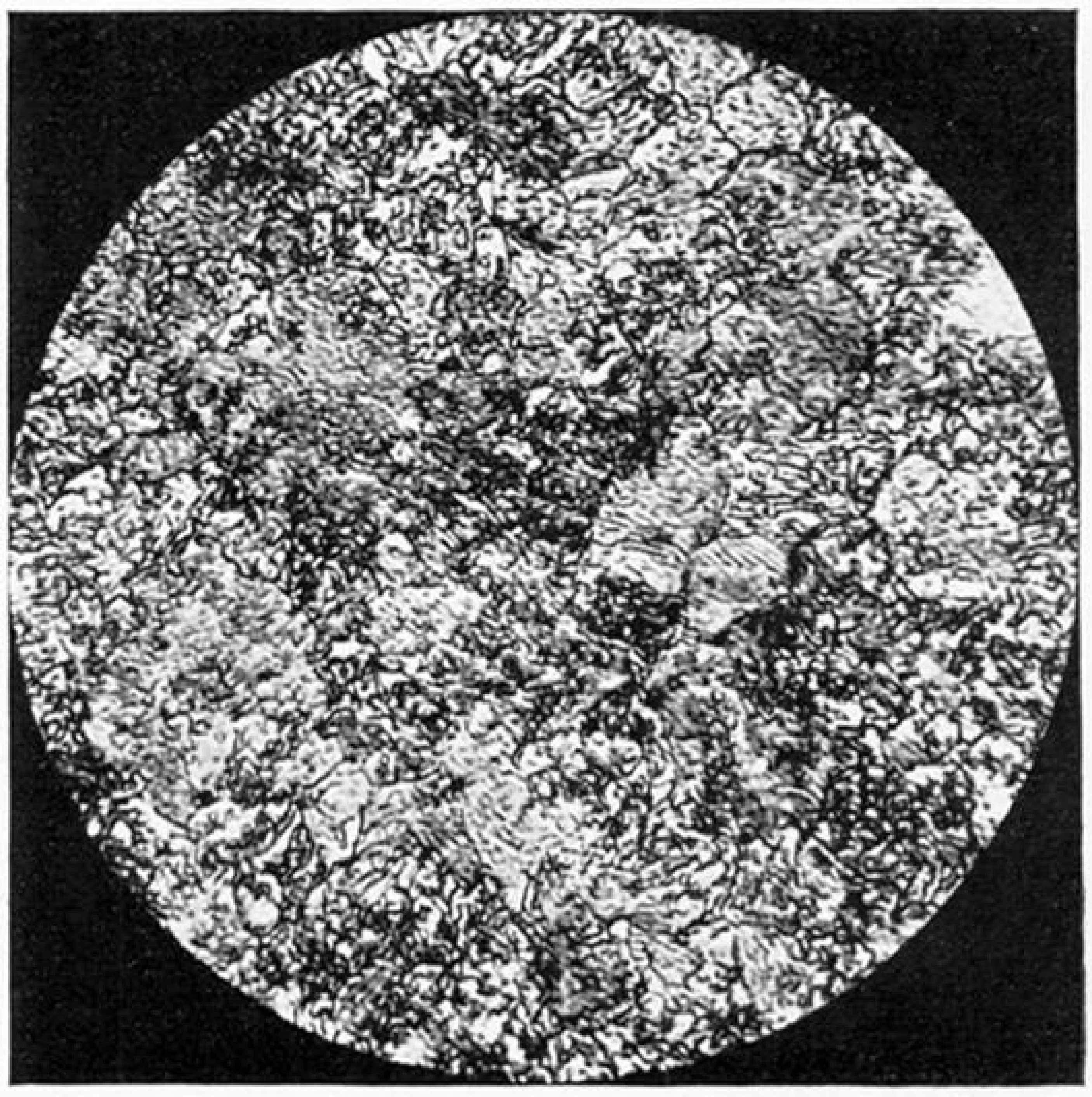

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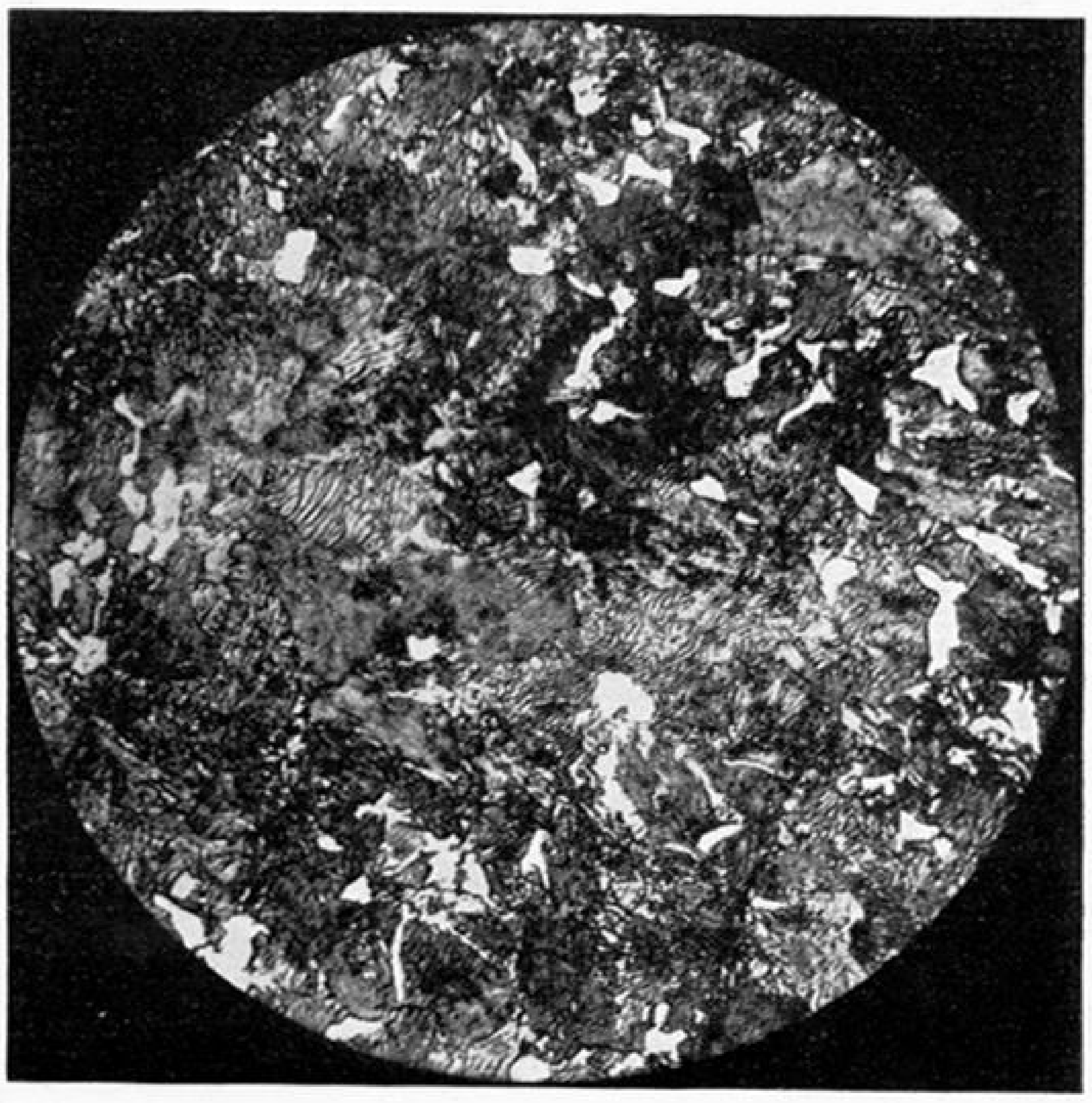

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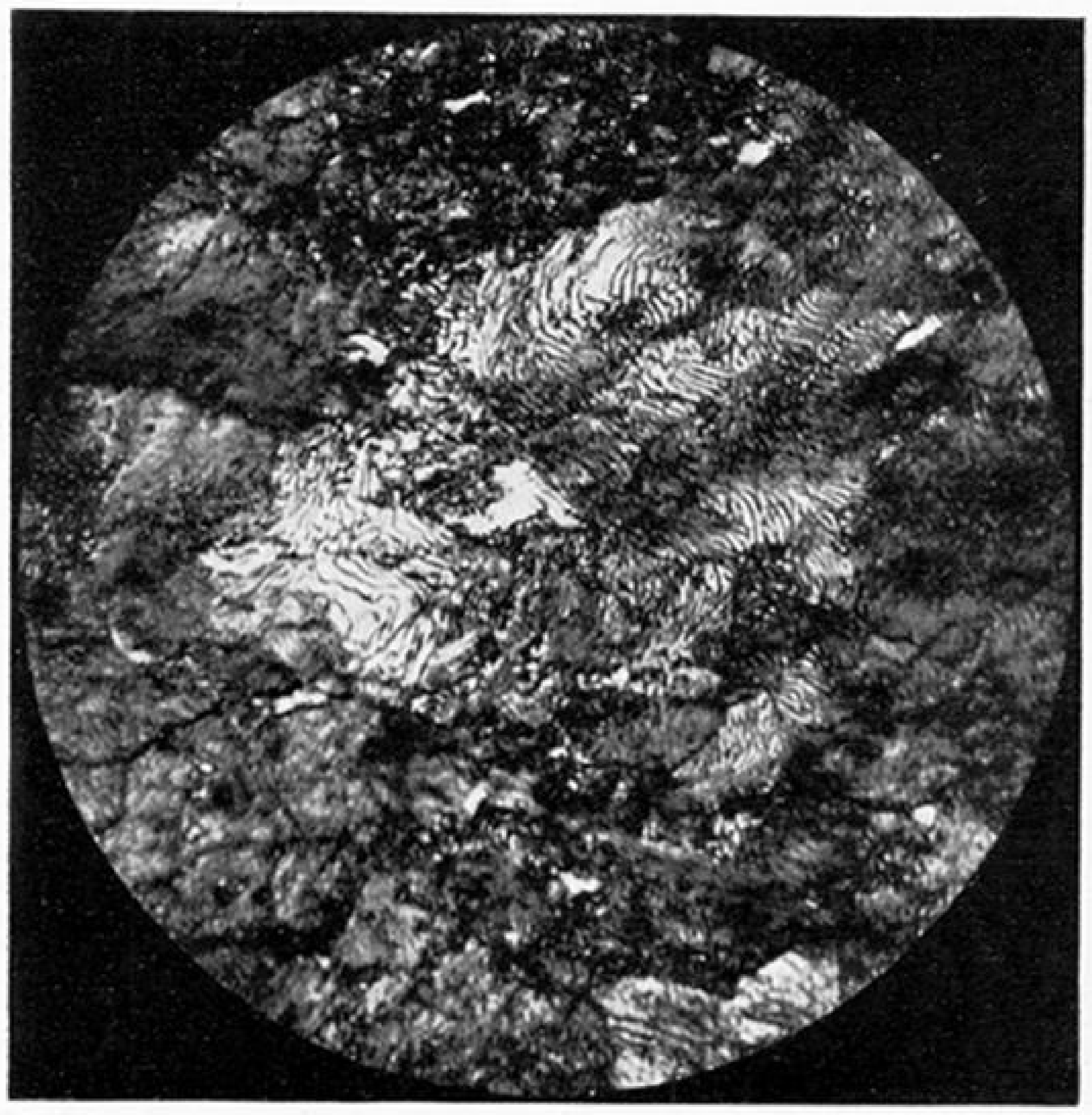

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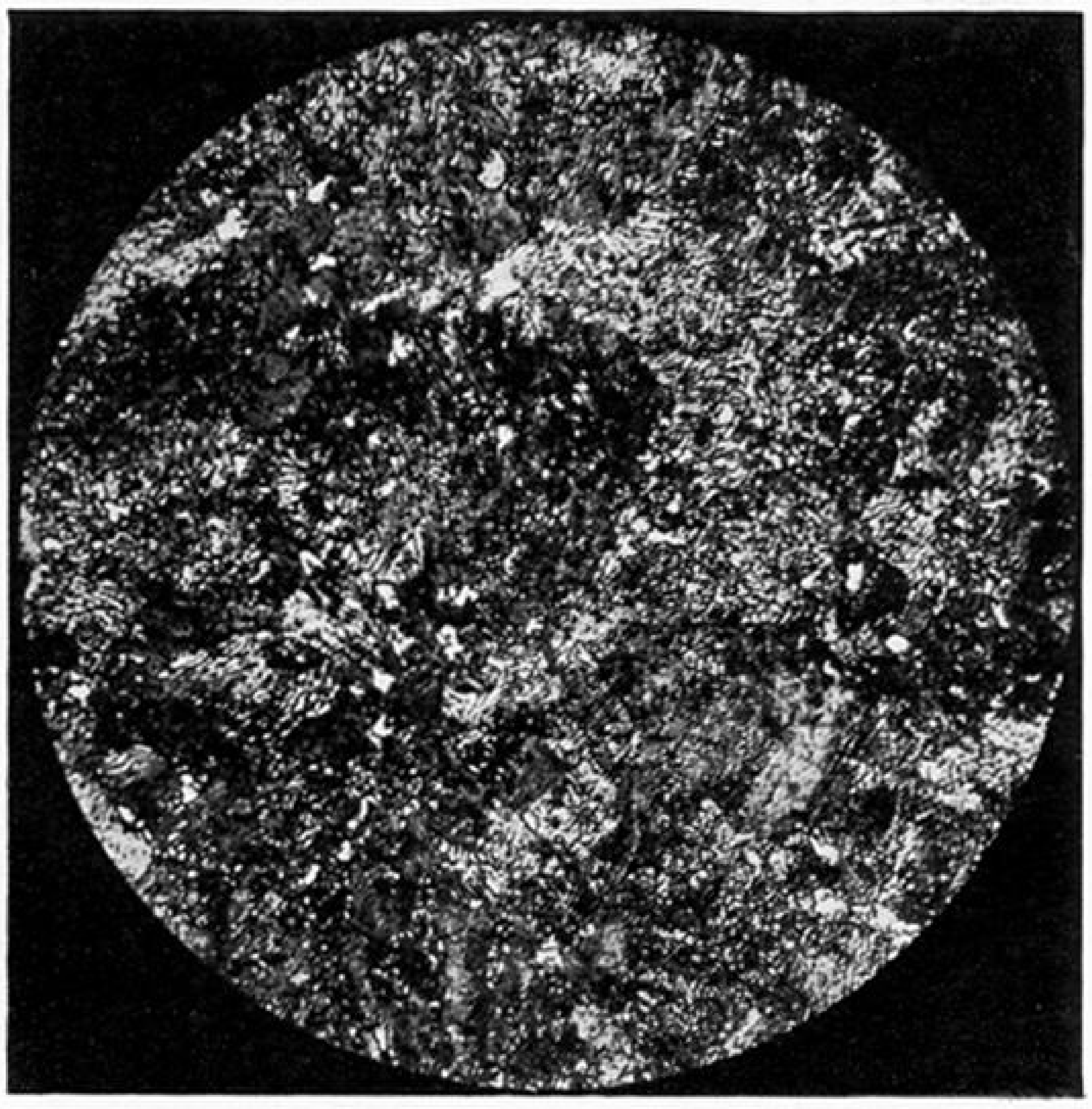

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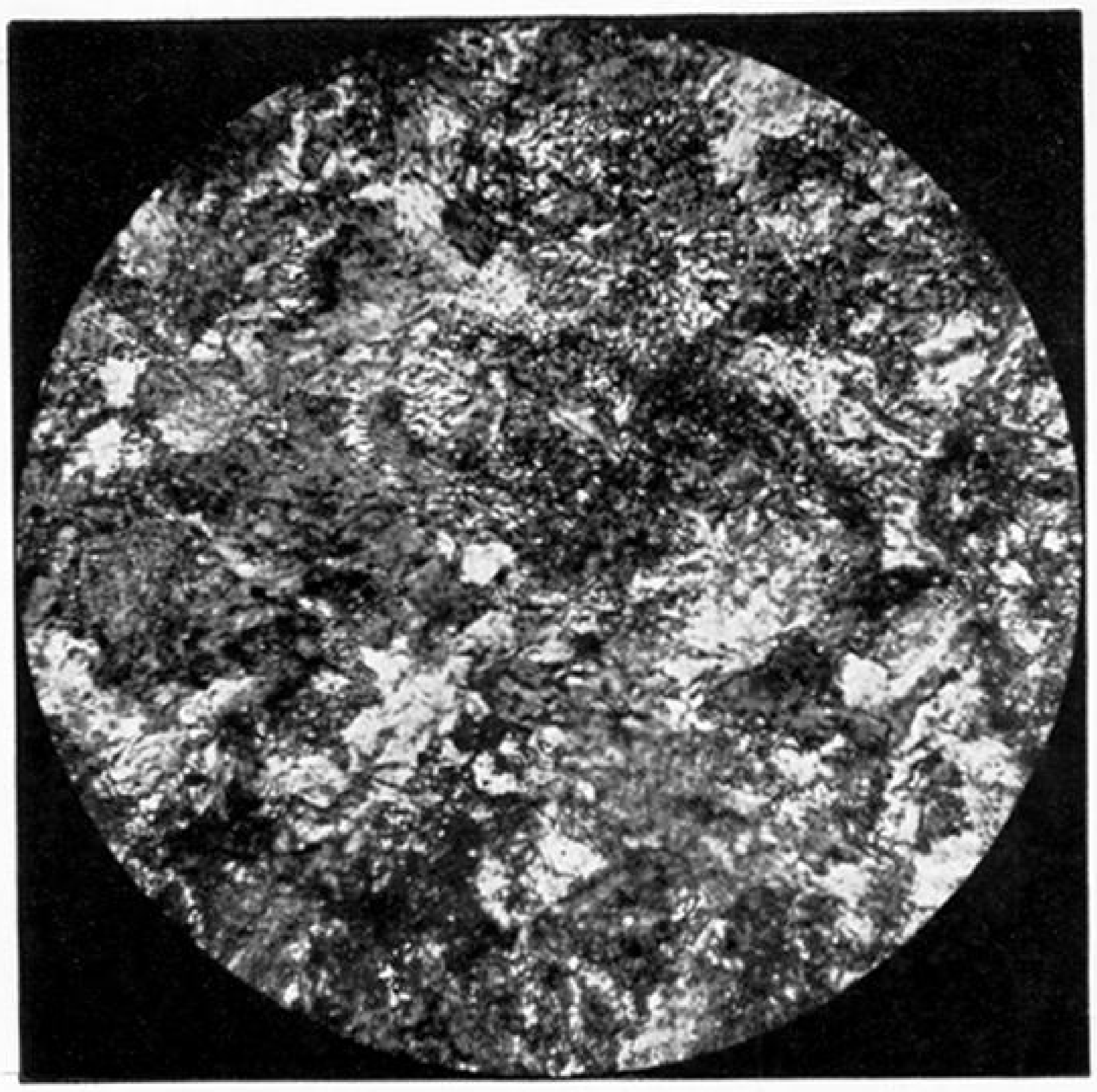

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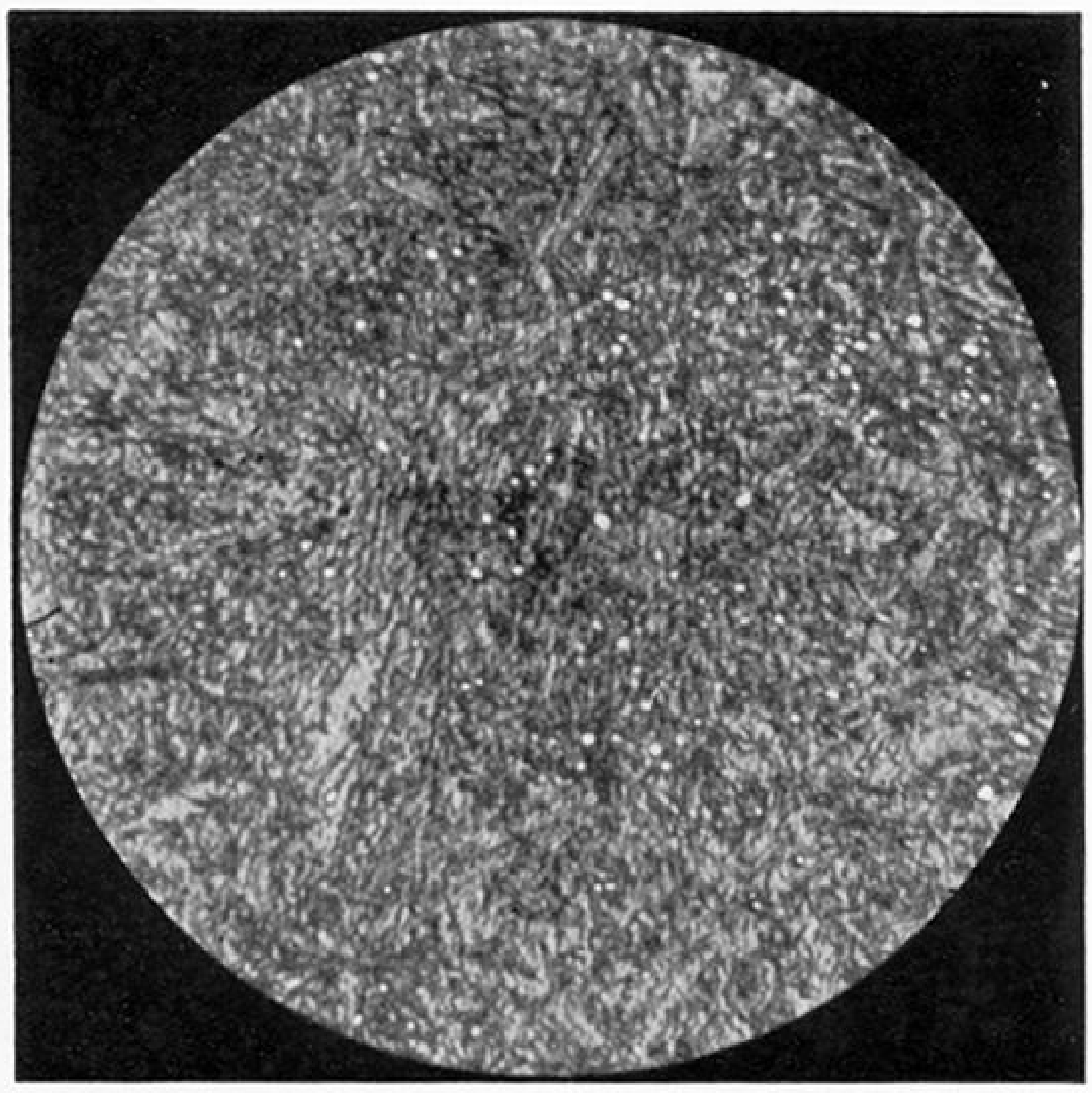

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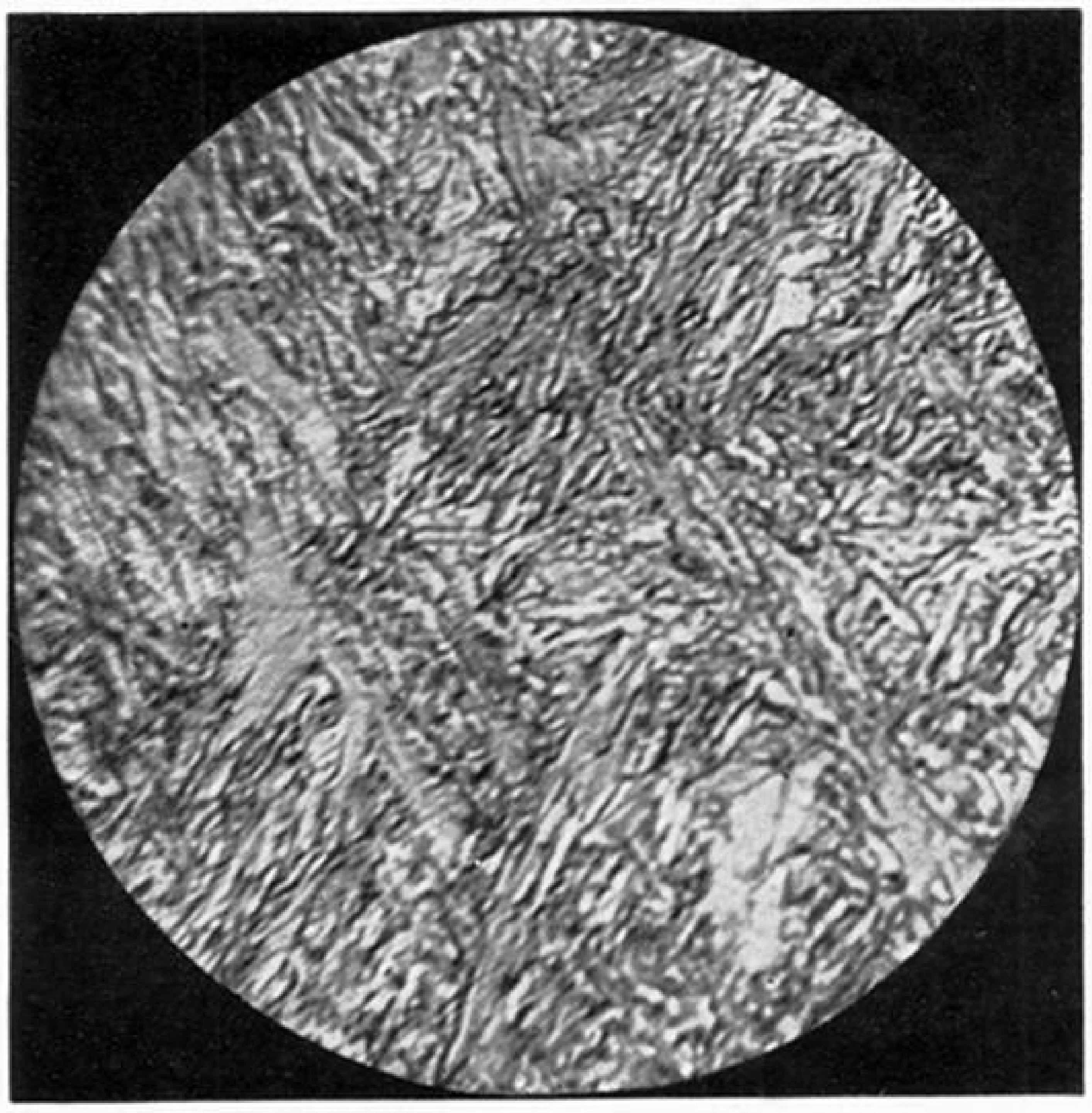

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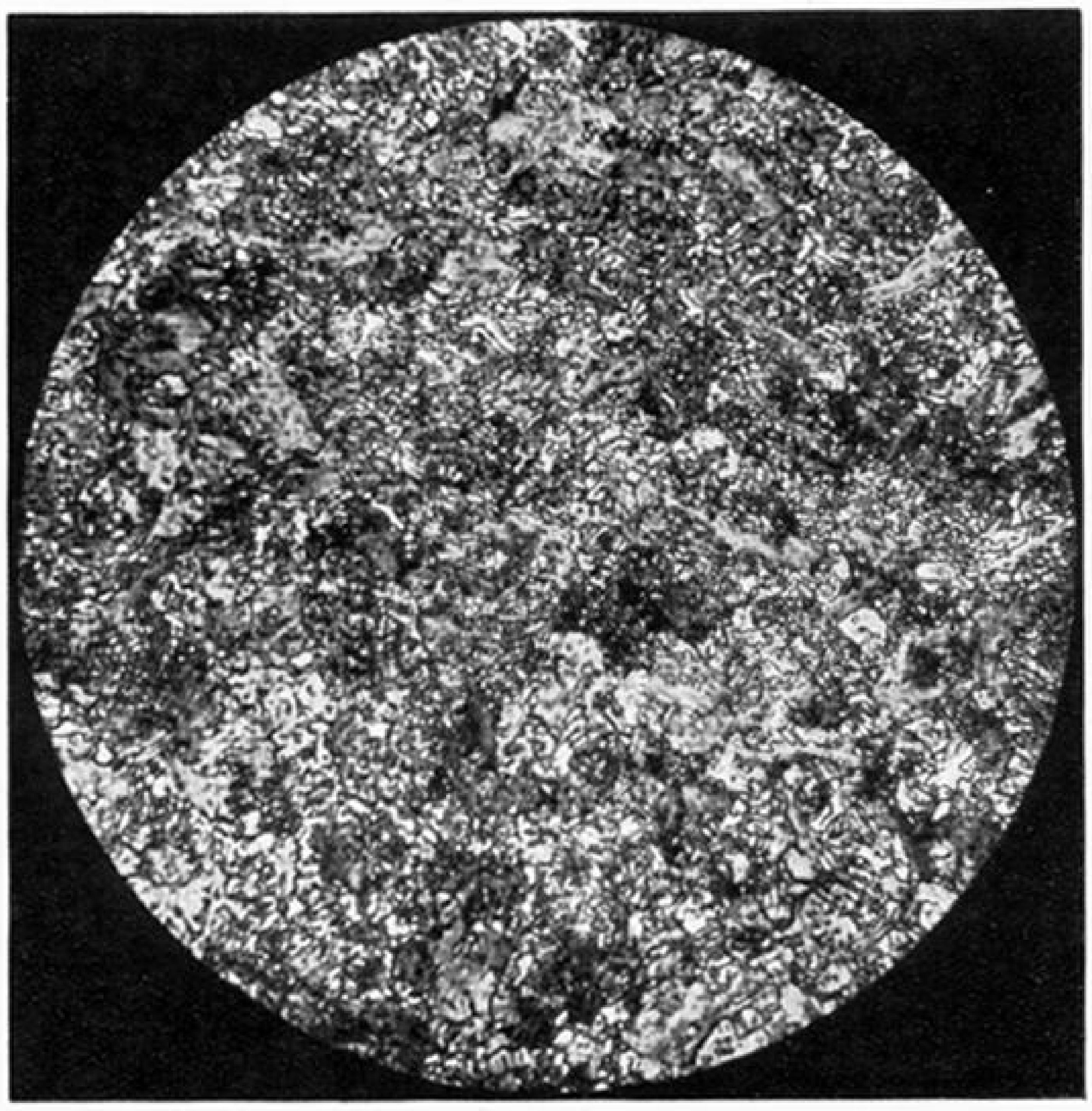

PM. 30. (X 400).