PHILOSOPHICAL TRANSACTIONS.

I. *On the Tempering of Iron Hardened by Overstrain.**

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Communicated by Professor EWING, *F.R.S.*

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[PLATE 1.]

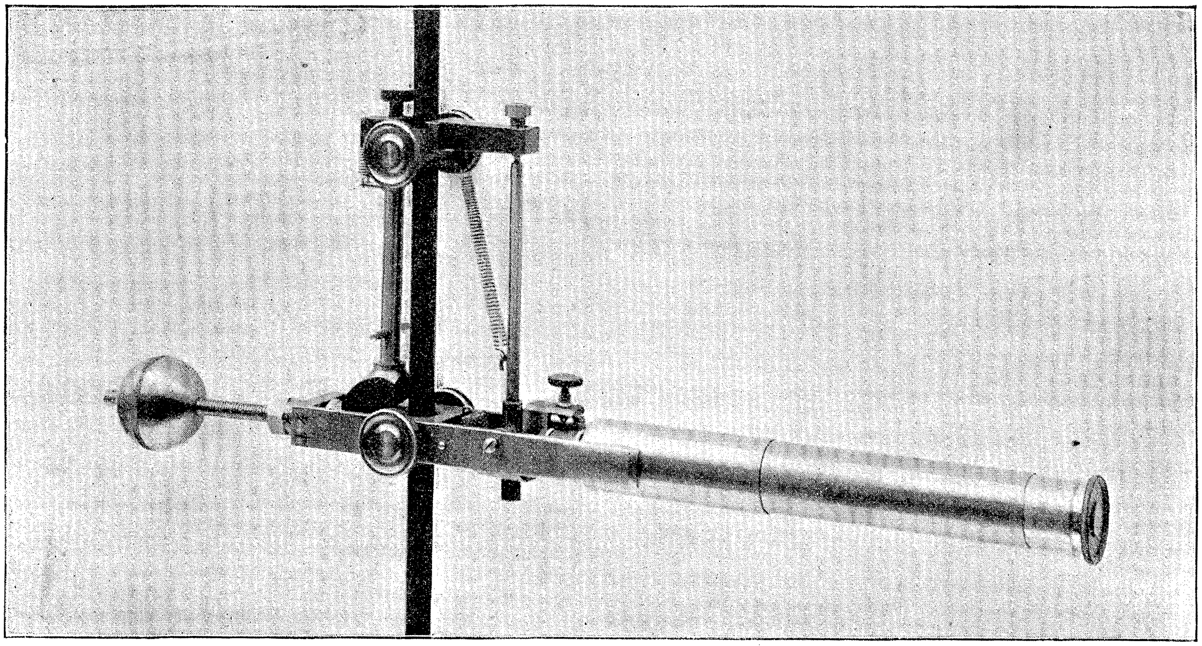
IT is well known that iron hardened by overstrain—for example, by permanent stretching—may have its original properties restored again by annealing, that is, by heating it above a definite high temperature and allowing it to cool slowly. Experiments to be described in this paper, however, show that if iron hardened by overstrain be raised to any temperature above about 300° C., it may be partially softened in a manner analogous to the ordinary tempering or "letting down" of steel which has been hardened by quenching from a red heat. This tempering from a condition of hardness induced by overstrain, unlike ordinary tempering, is applicable not only to steel but also to wrought iron, and possibly to other materials which can be hardened by overstrain and softened by annealing.

The experiments about to be described were all carried out on rods of iron or steel about $\frac{3}{8}$ths of an inch in diameter and 11 inches long, the elastic condition of the material being in all cases determined by means of tension tests. The straining and testing were performed by means of the 50-ton single-lever hydraulic testing machine of the Cambridge Engineering Laboratory, and the small strains of extension were measured by an extensometer of Professor EWING'S design, which gave the extension on a 4-inch length of the specimen to the $\frac{1}{100000}$th of an inch. This instrument, which is shown attached to a specimen in the following illustration, is of a design

* The work described in this paper was a continuation of that already described in a paper by the present author, "On the Recovery of Iron from Overstrain," 'Phil. Trans.,' A, vol. 193, 1899.

slightly modified from that of the larger extensometer fully described by Professor EWING in a paper "On Measurements of Small Strains in the Testing of Materials and Structures."*

For the purposes of tempering and annealing a gas furnace was employed, 2 feet in length. This furnace (manufactured by FLETCHER, RUSSELL, and Co., Warrington) is heated by means of a series of inclined bunsens entirely detached from the fire-clay portion of the furnace, so that regulation can be effected not only by altering the gas supply, but also by moving the bunsens nearer to or further from the orifices into



4-inch Extensometer.

which they play. The specimens were protected from direct contact with the flame by enclosing them in a thick porcelain tube. The temperature inside this tube was measured by means of a CALLENDAR'S direct-reading platinum-resistance pyrometer.† To ensure that the temperature recorded by the pyrometer was as accurately as possible that assumed by the specimen, readings were taken for both ends of the furnace, the specimen being moved from one end to the other to allow of the insertion of the pyrometer tube. In this reversal of positions the pyrometer tube in passing through the air was slightly cooled, so that the temperatures recorded immediaely after a change of positions were somewhat low. The following series of pyrometer readings is given by way of illustration :—

* 'Roy. Soc. Proc.,' vol. 58, April, 1895.

† "On the Construction of Platinum Thermometers," 'Phil. Mag.,' July, 1891; "On Platinum Thermometry," 'Phil. Mag.,' February, 1899. The instrument referred to above was made by the Cambridge Scientific Instrument Company, Limited.

Position of the Pyrometer.	Times in minutes.	Pyrometer readings.	
Pyrometer on the right	0	562° C.	—
,, ,, ,, ...	2	582	—
,, ,, ,, ...	3	592	—
,, ,, ,, ...	4	599	Bunsens slightly removed.
Pyrometer on the left	7	574° C.	—
,, ,, ,, ...	8	580	—
,, ,, ,, ...	10	584	Bunsens slightly closer on the left.
,, ,, ,, ...	12	595	—
Pyrometer on the right	13	597° C.	—
,, ,, ,, ...	14	605	Bunsens slightly removed.
,, ,, ,, ...	15	605	—
Pyrometer on the left	16	598° C.	—
,, ,, ,, ...	17	607	Gas supply turned off.
,, ,, ,, ...	18	604	—

From the above series of readings the specimen in the furnace would be said to have been heated to 605° C.

Preliminary Examination of the Material in the State as supplied.

The elastic properties of the materials to be employed were examined not only in the usual fashion by breaking a specimen in the testing machine, and recording the breaking load and the ultimate elongation, but also in a manner which has already been described in a paper by the present author on the recovery of iron from overstrain.* Diagram No. 1 of the present paper illustrates this method of examination, the material examined being a rod of steel rather under half an inch in diameter.

A specimen about a foot long was cut from this rod, and was turned down in the centre for a length of 5 inches to a diameter just over $\frac{3}{8}$ths of an inch. Sufficient length was left unturned at each end to enable the specimen to be securely gripped in the jaws of the testing machine. The diameter of the turned portion of the specimen was then accurately measured; a 4-inch length was marked off by means of a marking instrument of Professor EWING's design; the extensometer was attached to this 4-inch length, the specimen was put into the testing machine, and load was applied. Extensometer readings were taken after the addition of every ton per

* The diagram in 'Phil. Trans.,' A, vol. 193, p. 31, 1899, shows this method of examining iron and steel.

sq. inch of load until higher stresses were obtained, and then readings were taken after every half ton, and while each half ton was being slowly added the eye was kept at the microscope of the extensometer in order to detect as accurately as possible the load at which large plastic yielding commenced. Curve No. 1, Diagram 1 (p. 6), shows that such yielding began at the high load of 38 tons per sq. inch, a well-defined yield-point being obtained at that stress.

In plotting the curves of the present example and of all other diagrams in this paper, the method of "shearing back" the curves, which was adopted on Professor EWING's suggestion in the author's previous paper on Recovery from Overstrain, has again been employed.* This method consists in diminishing all extensions before plotting by an amount proportional to the loads producing them. By this means curves which would otherwise stretch far across the paper in the direction of extensions are brought more nearly into an upright position, so that a large scale for the measurement of extensions may be retained without an inconvenient amount of space being occupied. All the curves in this paper have been "sheared back" by the same amount; $\frac{110}{100000}$ths of an inch have been deducted from the extension of a 4-inch length for every 4 tons of stress. For example, the extensometer readings for Curve 1, Diagram 1, corresponding to the stresses of 4, 8, and 12 tons per sq. inch, were 120, 240, and 362 respectively. The numbers actually plotted were 10, 20, and 32.

It should be remarked that in all the diagrams of this paper, the origin for the measurement of extensions has been displaced by an arbitrary amount between each curve and the next in the series. This was merely to keep the various curves distinct, and to facilitate comparison.

The yielding which is shown by Curve No. 1, Diagram 1, to have begun at the stress of 38 tons per sq. inch soon became very rapid under this stress. The load was therefore slightly reduced† until a rate of extension convenient for observation was obtained, and it was then found that the stretching continued at a more or less constant speed (the lever of the testing machine being kept floating) for a considerable time, and then abruptly stopped; or, to be more accurate, rapid extension then abruptly changed into very slow creeping. The replacement of the full load of 38 tons was found to produce comparatively little further extension.

This yielding which takes place at the yield-point does not occur simultaneously throughout the length of the specimen. The material at some point in the bar yields and the yielding is observed to spread. The yielding at any point increases the intensity of the stress at neighbouring points of the bar, so that adjacent portions of material yield, and the action is transmitted piecemeal throughout the whole length of the specimen. With unturned material the progress of this yielding can be observed in the skin of oxide cracking and springing off as the

* In 'Phil. Trans.,' A, vol. 193, p. 12, 1899, a full account of "shearing back" is to be found.

† With Lowmoor iron it was found that the load at the yield-point could sometimes be reduced by almost two tons/in^2 without causing the yielding at the yield-point to cease.

action travels along the bar.* It was usually found with unturned specimens that the yielding started in the grips of the testing machine, and spread upwards or downwards as the case might be. Sometimes yielding was observed to begin at both ends and to travel towards the centre of the bar.

The amount of stretching which occurred at the yield-point shown in Curve 1, Diagram 1 was very considerable, the specimen having been given a permanent extension of 0·13 of an inch on a 4-inch length. The horizontal part of Curve No. 1 would thus require to be continued for over 8 feet in order to represent this yielding to the scale employed in the diagram.

After Curve No. 1 had been determined and the load removed, the reduced diameter of the specimen was measured and the new area of section was calculated. A 4-inch length was again marked off by means of the marking instrument, the extensometer was readjusted, and the load was reapplied in tons per sq. inch of actual section.† Extensometer readings were taken after the addition of every 4 tons per sq. inch, and Curve No. 2 was plotted from these readings. This curve shows the semi-plastic nature of the material immediately after overstrain.

It was noticed in previous experiments on the recovery from overstrain, that different steels, after tensile overstrain, recovered their elasticity at very different rates; so it was decided to examine the rate at which the material in question recovered from the semi-plastic condition illustrated by Curve 2, Diagram 1. The specimen was simply allowed to rest and was tested at intervals. Curves Nos. 3 and 4 illustrate the progress made towards recovery of elasticity, one and three-quarter days, and two weeks after overstrain, respectively.

In order to effect perfect recovery of elasticity, the specimen was put in the gas furnace described above and was heated until the pyrometer recorded about 200° C. It is probable that a few minutes at the temperture of boiling water would have been nearly though perhaps not quite as effective in restoring the lost elasticity.‡ After cooling the specimen was tested by reloading and carefully increasing the load above its previous maximum amount. A well-defined yield-point was obtained (as is shown by Curve No. 5, Diagram 1) at the stress of 49 tons per sq. inch, the yield-point having been raised by the large step of 11 tons per sq. inch. The amount by which the material yielded at this second yield-point was, to the nearest $\frac{1}{100}$th of an inch, the same as that by which it yielded at the primary yield-point, namely, by 0·13 of an inch on the 4-inch length.

The material after this second overstrain was once more in the semi-plastic state,

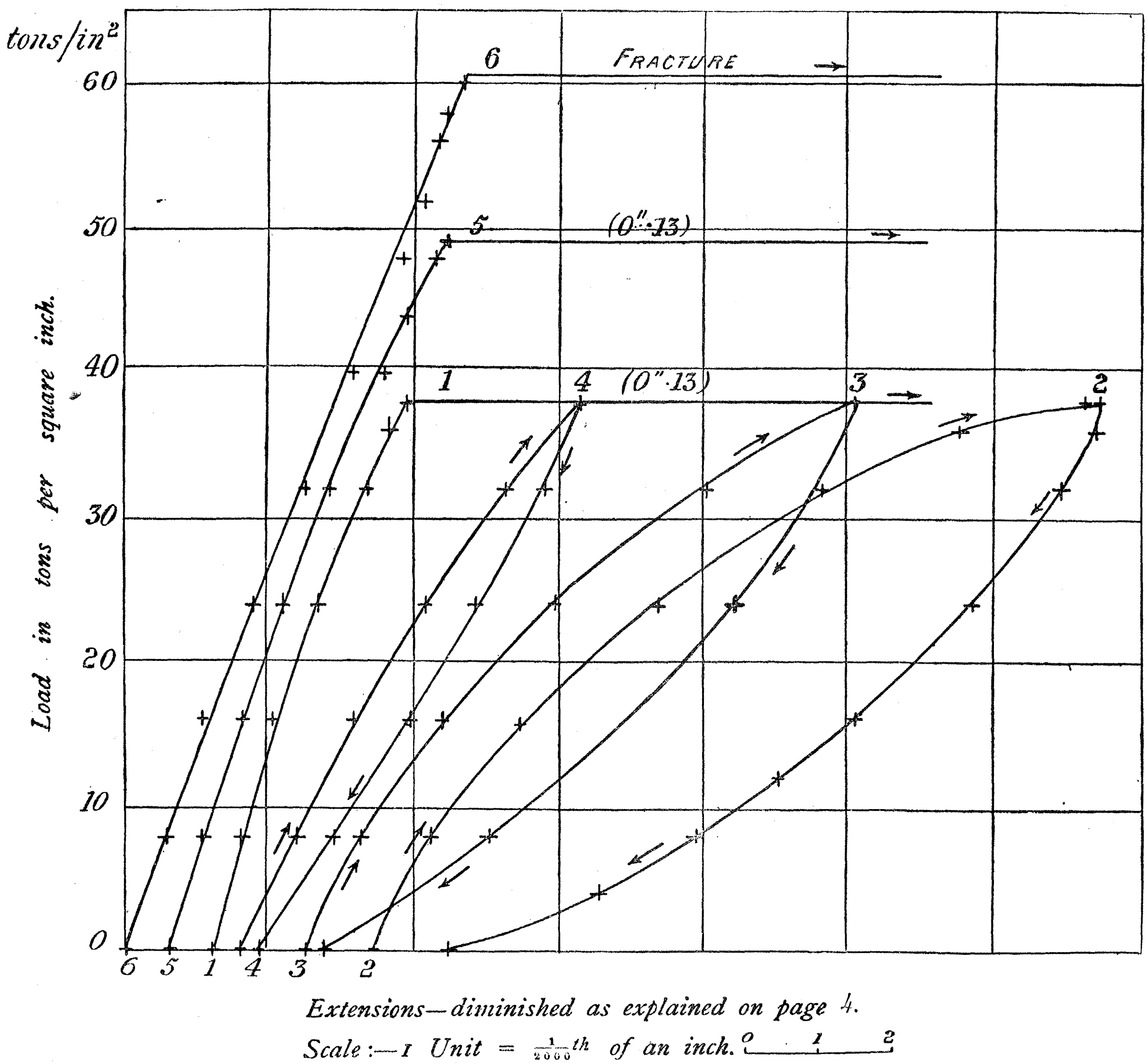
* Professor EWING, in the paper referred to above, "On Measurements of Small Strains," &c., has already observed that yielding may begin near one end of the specimen and gradually spread throughout the length, 'Roy. Soc. Proc.,' vol. 58, p. 135, April, 1895.

† This procedure was adopted throughout the course of the work. Whenever a yield-point had been passed, the specimen was re-measured and the loading altered to suit the new area of section.

‡ "On the Recovery of Iron from Overstrain," 'Phil. Trans.,' A, vol. 193, p. 22, 1899.

so to effect recovery of elasticity the specimen was, as before, heated to about 200° C. and slowly cooled. It was known as the result of earlier experiments that the yield-point had been raised by this process through a second step of 11 tons,*

Diagram No. 1. (Steel as supplied.)

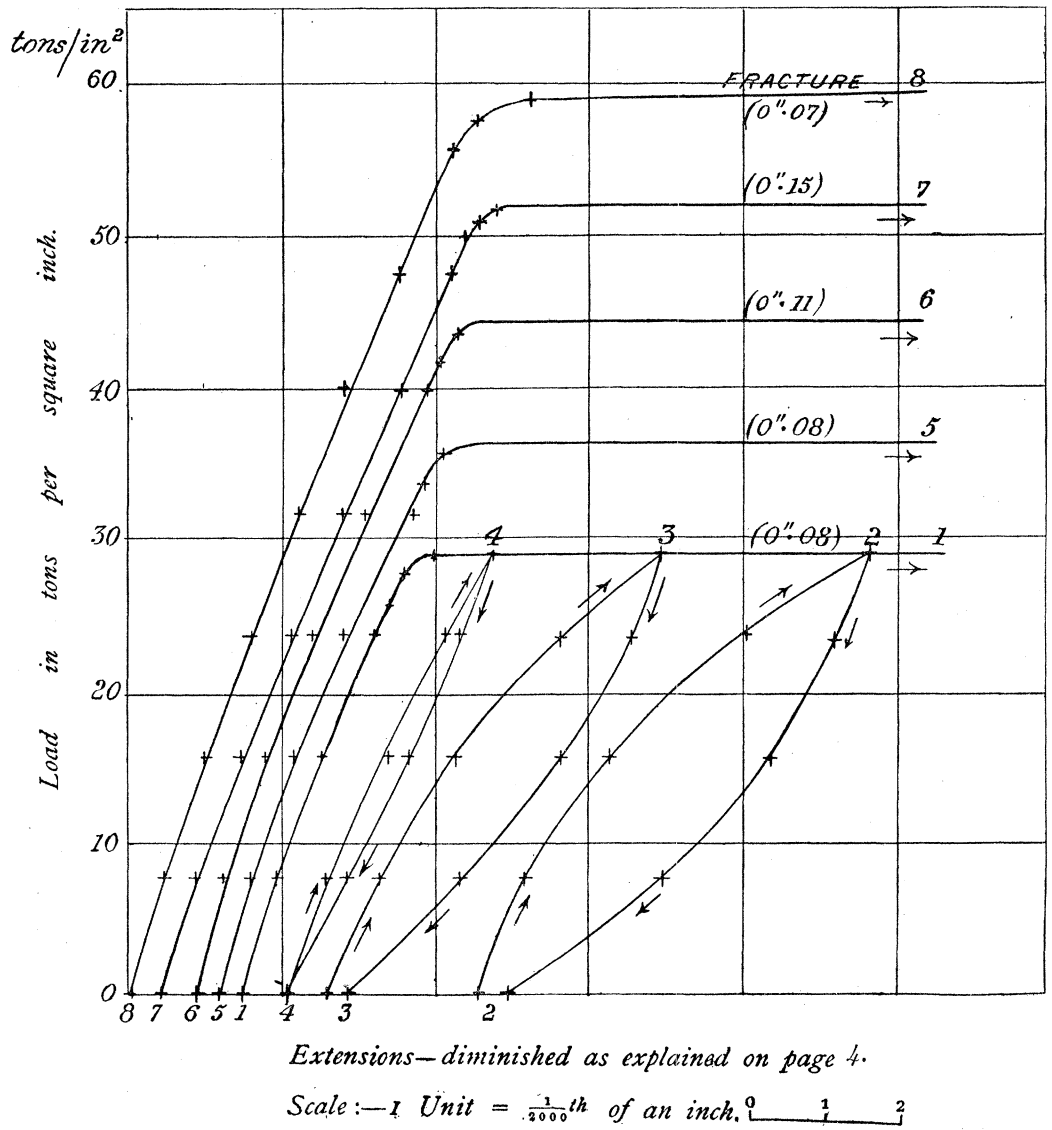


Curve No. 1—Primary test.	Curve No. 4—2 weeks after No. 1.
„ „ 2—Shortly after No. 1.	„ „ 5—After heating to 200° C.
„ „ 3—1¾ days „ „ 1.	„ „ 6— „ „ 200° C.

so that the specimen should not yield until a stress of 60 tons per sq. inch had been applied. Curve No. 6, Diagram 1 shows that the specimen bore the stress of 60 tons, but that with 60½ tons per sq. inch a yield-point and fracture occurred.

* "On the Recovery of Iron from Overstrain," 'Phil. Trans.,' A, vol. 193, p. 34, 1899.

Diagram No. 2. (Annealed Steel.)



Curve No. 1—Primary test.
" " 2—Shortly after No. 1.
" " 3—1¾ days " " 1.
" " 4—2 weeks " " 1.

Curve No. 5—After heating to about 300° C.
" " 6— " " " 300° C.
" " 7— " " " 300° C.
" " 8— " " " 300° C.

The Effect of Annealing.

It was found that the process of annealing altered in an interesting fashion the elastic properties of the material whose virgin properties are illustrated in Diagram No. 1. The primary yield-point was found to be considerably lowered by annealing, and the step by which the yield-point was raised in consequence of overstrain and

recovery from overstrain was decidedly reduced. Diagram No. 2 gives the history of a specimen of this steel, which was first of all annealed by heating for a few minutes to about 750° C. with a slow cooling, and was then subjected to series of operations exactly similar to that described for Diagram No. 1.

A comparison of Diagrams No. 1 and No. 2, or an examination of the following tables of extensometer readings, clearly shows the effect produced on the elastic properties of the material by the process of annealing. Only a few of the readings taken to obtain the various curves of the two diagrams will be tabulated for the sake of comparison; and it should be mentioned that the curves were in many cases obtained from second loadings of the material at the varies stages of the experiments.

Readings for Diagram No. 1. (Steel as supplied.)

Load in tons/sq. inch.	Extensometer readings. (Unit = $\frac{1}{100000}$th of an inch.)					
	Curve 1.	Curve 2, zero time.	Curve 3, $1\frac{3}{4}$ days.	Curve 4, 2 weeks.	Curve 5, 200° C.	Curve 6, 200° C.
0	0	0	0	0	0	0
8	240	262	260	260	242	246
16	484	548	533	519	490	494
24	734	856	832	789	738	746
32	986	1192	1154	1061	990	1004
36	1112	1396	—	—	—	—
38	Yield-point	1540	1426	1281	—	—
40	—	—	—	—	1248	1256
44	—	—	—	—	1374	1386
48	—	—	—	—	1506	1513
49	—	—	—	—	Yield-point	
52	—	—	—	—	—	1638
56	—	—	—	—	—	1758
60	—	—	—	—	—	1884
$60\frac{1}{2}$	—	—	—	—	—	Fracture

Curves 5 and 6 relate to tests made after exposing the material to a temperature of 200° C. for a few minutes.

Readings for Diagram No. 2. (Annealed Steel.)

Load in tons/sq. inch.	Extensometer readings. (Unit = $\frac{1}{100000}$th of an inch.)							
	Curve 1.	Curve 2, zero time.	Curve 3, $1\frac{3}{4}$ days.	Curve 4, 2 weeks.	Curve 5, 300° C.	Curve 6, 300° C.	Curve 7, 300° C.	Curve 8, 300° C.
0	0	0	0	0	0	0	0	0
4	122	—	—	—	120	120	122	120
8	248	254	258	251	241	241	249	241
16	498	532	528	510	491	491	498	490
24	751	838	820	770	746	742	751	740
29	932 and yield-point	1060	1022	935				
32	—	—	—	—	1010	992	1010	991
36	—	—	—	—	1146	1122	1140	
$36\frac{1}{2}$	—	—	—	—	1250 and yield-point			
40	—	—	—	—	—	1256	1264	1242
44	—	—	—	—	—	1387	1391	
$44\frac{1}{2}$	—	—	—	—	—	1406 and yield-point		
48	—	—	—	—	—	—	1520	1499
50	—	—	—	—	—	—	1581	
52	—	—	—	—	—	—	1661 and yield-point	1627
56	—	—	—	—	—	—	—	1756
58	—	—	—	—	—	—	—	1828
59	—	—	—	—	—	—	—	1880
$59\frac{1}{2}$	—	—	—	—	—	—	—	Fracture

Curve No. 1 of Diagram 2 shows that annealing has had the effect of lowering the yield-point of the material by about 9 tons per sq. inch. With the virgin material the primary yield-point occurred at about 38 tons per sq. inch, with the annealed material at 29 tons per sq. inch. The stretching which occurred at the yield-point was also less in the case of the annealed material, the permanent extensions in the two cases being respectively 0·13 and 0·08 of an inch on the 4-inch lengths.

A comparison of Curves 2, 3, and 4 of Diagram No. 1, with Curves 2, 3, and 4 of Diagram No. 2, shows that immediately after overstrain annealed material exhibits rather less hysteresis than the same metal not previously annealed; and that recovery from the semi-plastic condition induced by overstrain takes place rather more rapidly in the case of the material which has been first of all annealed.

Curve No. 5 and the remaining three curves of Diagram No. 2 show that with an annealed specimen the step by which the yield-point is raised in consequence of tensile overstrain and recovery from overstrain is about $7\frac{1}{2}$ tons per sq. inch, and that *four* such steps can be obtained before fracture occurs at about $59\frac{1}{2}$ tons per sq. inch. With the material in the condition as supplied, fracture occurred at $60\frac{1}{2}$ tons per sq. inch after *two* steps of about 11 tons.

It may be of interest to refer to the amount of stretching which occurred at the various yield-points shown in Diagram No. 2. At the first yield-point the permanent set was found to be 0·08 of an inch on the 4-inch length, at the second it was again 0·08 of an inch, at the third it was 0·11, at the fourth 0·15, and at the fifth fracture occurred and only local yielding of about 0·07 of an inch was obtained. Although the extensions at the third and fourth yield-points were thus greater than those at the first and second, it is probable that theoretically there need have been no such difference. Had it been possible to remove the load from each little portion of the specimen as soon as the yielding which occurs at a yield-point had spread throughout that portion of material, then probably the yielding at the third and fourth yield-points would not have been different from that at the first two. The extra extension at the higher yield-points was in all likelihood due to creeping, which continued after the break-down which occurs at a yield-point had taken place. In fact the elongation obtained at the fourth yield-point shown in Diagram No. 2 would have been greater still had not the load been removed shortly after the large yielding action had spread throughout the length of the specimen. Had this not been done, creeping would have continued, and probably fracture would have supervened, for previous experiments had shown that there was considerable danger of fracture occurring when a yield-point was passed at a high stress.*

The total elongation of the specimen whose history is given in Diagram 2 was thus 0·49 of an inch, or rather over 12 per cent. on a 4-inch length. The breaking load was $59\frac{1}{2}$ tons per sq. inch. Another specimen of this material which was annealed and then broken by the testing machine in the usual fashion, that is, without allowing intermediate recoveries of elasticity to take place, gave an ultimate strength of slightly over 44 tons per sq. inch, with an elongation of about 26 per cent. on a 4-inch length.

Comparison of Two Materials.

The following comparison of the material whose elastic properties have just been described, with that employed previously in the work on recovery from overstrain, which has been referred to more than once already, may be of interest. The chemical analyses of these two materials were kindly supplied by Messrs. EDGAR ALLEN and Co., Limited, Sheffield. They are as follows:—

* "On the Recovery of Iron from Overstrain," 'Phil. Trans.,' A, vol. 193, p. 35, 1899.

	Steel examined in the present paper ($\frac{1}{2}$-inch rod).	Steel used previously (1-inch rod).
Carbon	0·35	0·430
Silicon	0·102	0·112
Sulphur	0·063	0·010
Phosphorus	0·034	0·016
Maganese	1·16	0·450
Iron (by difference) ...	98·291	98·982
	100·000	100·000

The elastic properties of the two materials are compared in the table given below. In each case the results of an ordinary tensile test are given first, and then the data obtained by testing the material in the manner illustrated by Diagram 1 or Diagram 2 of this paper. In the second last column of the table there are tabulated the number of times the yield-point was raised in consequence of overstrain and recovery from overstrain when the material was tested in the manner just referred to, and in the last column the amount (in tons per sq. inch) by which the yield-point was raised each time. By way of illustration, in Diagram 1 the yield-point is shown to have been raised twice by a step of about 11 tons per sq. inch, while in Diagram 2 it is shown to have been raised four times by a step of $7\frac{1}{2}$ tons per sq. inch. In an ordinary tensile test of course the specimen is not strained by steps.

Material.	Diameter of a turned specimen.	Yield-point.	Breaking stress.	Ultimate extension.	No. of steps.	"Step."
$\frac{1}{2}$-in. steel rod, as supplied	0·40 of an in.	$37\frac{1}{2}$ tons/sq. in.	47 tons/sq. in.*	23 per cent. on 4 ins.*	—	—
	0·40 ,, ,,	$37\frac{1}{2}$,, ,, ,,	$60\frac{1}{2}$,, ,, ,,	8 or 9 ,, ,, ,,	2	11 tons/sq. in.
$\frac{1}{2}$-in. steel rod, annealed	0·44 ,, ,,	29 ,, ,, ,,	44 ,, ,, ,,	26 ,, ,, ,,	—	—
	0·40 ,, ,,	29 ,, ,, ,,	$59\frac{1}{2}$,, ,, ,,	12 ,, ,, ,,	4	$7\frac{1}{2}$ tons/sq. in.
1-in. steel rod, as supplied	0·80 ,, ,,	23 ,, ,, ,,	$36\frac{1}{2}$,, ,, ,,	23 per cent. on 8 ins.	—	—
	0·79 ,, ,,	23 ,, ,, ,,	$45\frac{1}{2}$,, ,, ,,	10 ,, ,, ,,	4	$5\frac{1}{2}$ tons/sq. in.

From this table it will be seen that the 1-inch steel rod as supplied resembled in elastic properties the $\frac{1}{2}$-inch rod in the annealed state, and not in the condition as supplied by the makers.

* These two figures were not obtained by experiment, but were estimated from results obtained with material very similar to the above, but containing more silicon (0·6 per cent.) and $\frac{3}{8}$ inch in diameter. This thinner material gave when in the condition as supplied a yield-point at $36\frac{1}{2}$ tons/sq. inch and broke under an ordinary tensile test at $43\frac{1}{2}$ tons with an elongation of 16 per cent. on 4 inches. After annealing, the yield-point occurred at 25 tons/sq. inch and fracture at $39\frac{1}{2}$ tons/sq. inch, the elongation being $19\frac{1}{2}$ per cent. on a 4-inch length.

Microscopic Examination of Steel.

The two steels whose elastic properties have just been compared, and whose chemical analyses are given above, were also examined by means of the microscope. Three methods of examination were adopted, the first being the ordinary method by etching a polished surface with dilute nitric acid.

A smooth surface was prepared by means of commercial emery paper, the final polishing being done by wet rouge contained on a piece of chamois leather stretched over a rotating disc. All or nearly all the fine scratches left on the surface of the steel by the emery paper having been removed by the rouge, the surface was washed and dried, and then etched with dilute nitric acid (0·1 per cent. strength).

Figs. A and B* (Plate 1) show, under a magnification of 150 diameters and with vertical illumination, the appearance (after polishing and etching in this manner) of transverse sections of the $\frac{1}{2}$-inch steel rod used in the experiments described in this paper. Fig. A shows the structure of this steel when in the condition as supplied by the makers, that is when in the condition having the elastic properties illustrated by Diagram 1. Fig. B shows the structure of the same steel after annealing by heating for a few minutes to 750° C., that is, fig. B shows the structure of the steel after it had been brought by annealing into the condition having the elastic properties illustrated by Diagram No. 2 of this paper.

The photographs from which figs. A and B have been reproduced were taken three or four weeks after the specimens had been prepared and etched, so that the surfaces had become slightly tarnished. The tarnish, however, seemed only to emphasise the distinction between the two constituents, the "ferrite" and the "pearlite."

A comparison of figs. A and B shows that by annealing at 750° C. the structure of the $\frac{1}{2}$-inch steel rod had been considerably altered. After annealing the steel was much coarser grained than when in the somewhat hardened condition as supplied by the makers. This change produced by annealing on the dimensions of the micro-structure of steel has been often observed before.† Figs. A and B are given here for the sake of comparison with the change in elastic properties illustrated by Diagrams 1 and 2 of this paper. It had been thought that this change in elastic properties could be entirely accounted for on the supposition that the bars left the rolling mills at a comparatively low temperature (say a dull red heat), and had so become hardened by a species of overstrain. The microscopic examination illustrated

* Reproduced from photographs. The author is indebted to Mr. ROSENHAIN, of St. John's College, for photographing the micro-sections prepared for the paper, and also for information as to the methods of polishing and etching.

† For example, by OSMOND, "Méthode générale pour l'Analyse micrographique des Aciers au Carbone," 'Bulletin de la Soc. d'Encouragement,' Mai, 1895; by ARNOLD, "The Influence of Carbon on Iron," 'Proc. Inst. Civ. Eng.,' December, 1895; by STEAD, "The Crystalline Structure of Iron and Steel," 'Journ. of Iron and Steel Institute,' 1898.

by figs. A and B seems, however, to indicate that the change in the properties of the material has to be attributed more to a thermal cause. It is unlikely that the structure of the material could be changed back from the annealed condition (fig. B) to the hardened condition (fig. A) by purely mechanical means. Mechanical hardening is accompanied by distortion of the grains, not by change in their dimensions.

The second method of microscopic examination which was adopted may be classified as what OSMOND calls "un polissage-attaque." The process was discovered accidentally, and consists simply in rubbing a surface of steel polished with wet rouge in the manner described above, with ordinary moistened cocoa. The cocoa stains the pearlite areas of the steel, which are thrown into relief by the polishing, the effect being probably very analogous to that produced by the infusion of liquorice root, which OSMOND and others usually employ. Fig. C (Plate 1) shows, under a magnification of 150 diameters and with vertical illumination, the structure of the 1-inch steel rod whose properties are given in the preceding section of this paper; the surface examined was polished with emery and rouge in the ordinary manner, and then rubbed for a little while on a piece of chamois leather which had been moistened and covered with VAN HOUTEN's cocoa. The surface was also examined under a magnification of about 3000 diameters, and the beautiful laminated structure of the pearlite areas was thus very clearly shown. One series of the laminæ—the Sorbite series—were stained a brown colour, the other series remained bright. It was found that benzene removed the staining produced by the cocoa.

The specimens from which figs. A and B had been obtained were repolished to remove the effect of the etching by nitric acid, and were then stained with cocoa in the manner just described, and examined under magnifications of 150 and of 3000 diameters. The structures shown were much better defined than when produced by ordinary etching, and under the high magnification the laminated nature of the pearlite areas was clearly visible. The laminæ were more distinct in the annealed, that is in the coarser grained specimen.

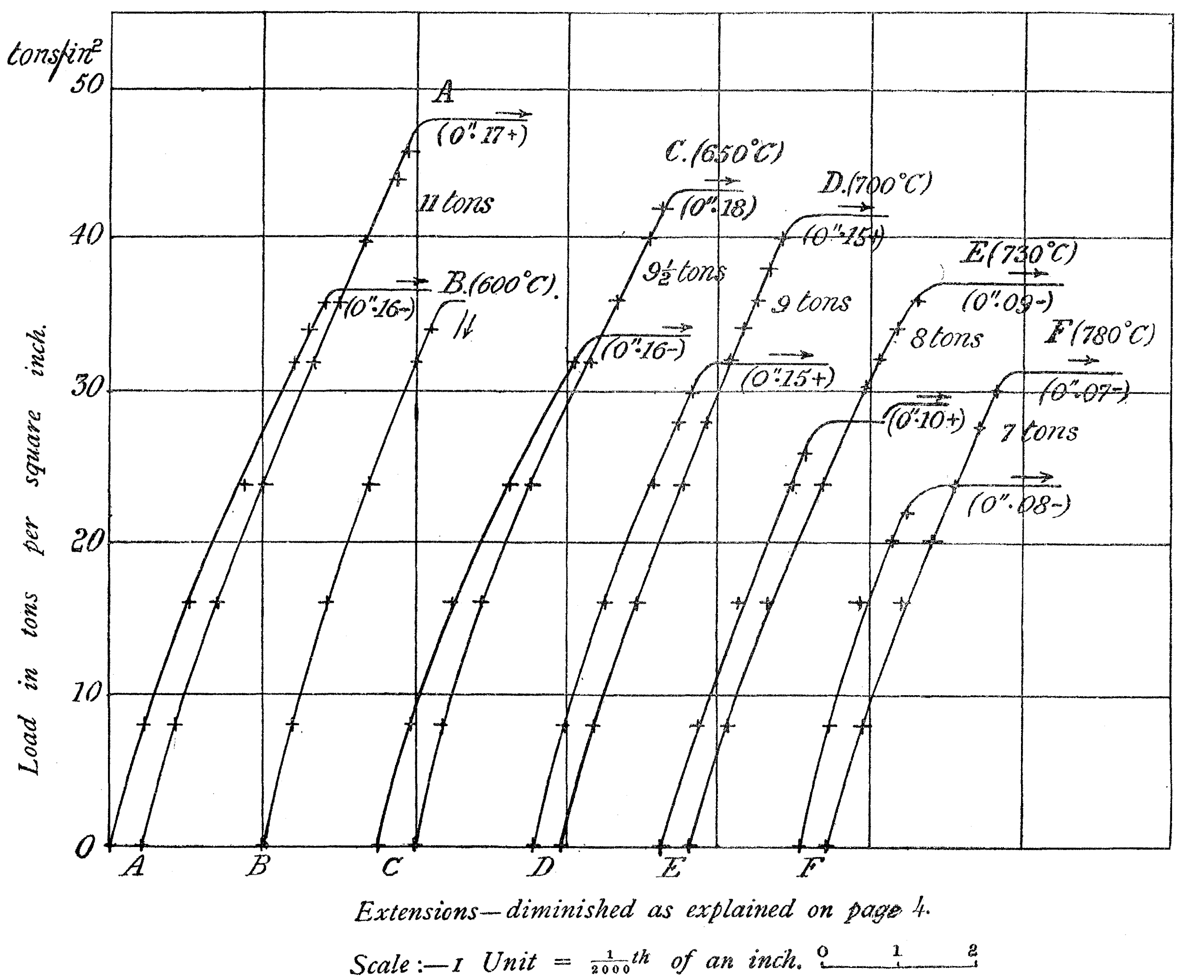
The third method of microscopic examination which was adopted consisted simply in polishing the steel in the ordinary way with emery and wet rouge, and then drying the surface and rubbing it on a leather pad coated with dry rouge. The polishing with wet rouge on chamois leather brought the surface into bas-relief, the rubbing on the dry pad filled the hollows with fine rouge, so that when examined under a magnification of 150 diameters the structure of the steel could readily be seen. The difference between the structures shown in figs. A and B was quite as clearly and accurately shown by this means as by etching or by staining, but of course under high magnification the nature of the constituents was not resolved.

The Tempering of Steel from the Condition as supplied.

It was found that the change in elastic properties shown by a comparison of Diagrams 1 and 2 to be produced by annealing, could be brought about gradually by heating the material to temperatures lower than that which is commonly known as an annealing temperature. Any temperature exceeding 600° C. was found sufficient to produce a distinct lowering of the primary yield-point and a reduction of the step by which the yield-point is raised in consequence of recovery from over-strain. Diagram No. 3 illustrates this gradual tempering of the material from the condition as supplied by the makers, that is, from the condition of high yield-point and large step.

Six specimens were employed to obtain the curves shown in Diagram 3, and these

Diagram No. 3. (Tempering of Steel from the condition as supplied.)



Curves A—Material as supplied.
,, B—After heating to 600° C.
,, C— ,, ,, ,, 650° C.

Curves D—After heating to 700° C.
,, E— ,, ,, ,, 730° C.
,, F— ,, ,, ,, 780° C.

were all taken from a rod of steel similar in quality to that used for Diagrams 1 and 2, but of a smaller diameter.* This rod, in the rough, was about $\frac{3}{8}$ths of an inch in diameter, but some of the specimens after being slightly turned down, except at the ends, measured only about 0·32 of an inch.

Specimen A was tested in the condition as supplied, and the two curves marked A in Diagram No. 3 show that the primary yield-point has occurred at $36\frac{1}{2}$ tons per sq. inch, and that after recovery from overstrain the yield-point has been raised by 11 tons per sq. inch.

The second specimen, B, was heated to 600° C. for a few minutes, slowly cooled, and then tested, with the result that creeping set in at the stress of 36 tons per sq. inch. The load was, however, immediately reduced, no time being allowed for the extension of the yield-point to take place. It had thus been shown, however, that 600° C. was sufficient to produce a very slight annealing action. This specimen, B, was again used to obtain the curves marked D in Diagram No. 3.

Specimen C was heated to 650° C. and slowly cooled. On testing, a yield-point was obtained at $33\frac{1}{2}$ tons per sq. inch, and the step by which the yield-point was raised after recovery from overstrain was found to be about $9\frac{1}{2}$ tons per sq. inch.

The curves marked D in Diagram 3 show that material which had been heated to 700° C. gave a yield-point at about $31\frac{1}{2}$ tons per sq. inch, and that the step by which the yield-point was raised by recovery from overstrain was about 9 tons per sq. inch.

Specimen E was raised to 730° C., and the yield-point was found to be thereby lowered to $28\frac{1}{2}$ tons per sq. inch and the step reduced to 8 tons; while specimen F, which was tested after being heated to 780° and slowly cooled, showed that 780° C. brought the primary yield-point to 24 tons per sq. inch, and reduced the step to 7 tons per sq. inch.

The extensions which occurred at the various yield-points shown in Diagram 3 are all marked within brackets in the diagram, and it will be noticed that the extensions at the yield-points obtained with any one specimen are approximately equal, while for different specimens these extensions become less and less as the primary yield-point is lowered and the step diminished in consequence of tempering or annealing at higher and higher temperatures. In the following table there will be found the various data obtained from the experiments which have just been described.

* Particulars of this material are given in a footnote on p. 11.

TABLE showing the Tempering of Steel from the condition as supplied.

Condition of the material.	Primary yield-point.	Extension at yield-points.	"Step."
A. As supplied	$36\frac{1}{2}$ tons/sq. inch	0″·16 on 4 inches	11 tons/sq. inch.
B. Annealed at 600° C. . .	36 ,,		
C. ,, 650° ,, . .	$33\frac{1}{2}$,,	0″·16 ,,	$9\frac{1}{2}$,,
D. ,, 700° ,, . .	$31\frac{1}{2}$,,	0″·15 ,,	9 ,,
E. ,, 730° ,, . .	$28\frac{1}{2}$,,	0″·09 ,,	8 ,,
F. ,, 780° ,, . .	24 ,,	0″·07 ,,	7 ,,

There is thus a relation between the yielding at the yield-point and the step by which the yield-point is raised in consequence of recovery from overstrain. This step does not depend on the actual extension which the material receives, for it was shown in the author's paper on "Recovery from Overstrain"* that a specimen could be stretched by any amount (by increasing the overstraining load to any extent) without altering the step by which the yield-point was raised above the previous maximum stress. The amount by which the yield-point is raised after restoration of elasticity, and the extension which occurs just at a yield-point, are thus definite properties of the material—properties which can be altered, at least in some cases, by thermal treatment.

In the experiments which have just been described the specimens were only kept for a few minutes at the annealing temperatures, and the times taken to heat up and to cool down were in all cases practically the same. As it was thought probable that a prolonged exposure to any temperature would have a greater effect than a short exposure to the same temperature, the following experiment was tried:—

A specimen of the same material as was used to obtain Diagram 3 was raised to 700° C., slowly cooled, and loaded to 31 tons per sq. inch. No yield-point was passed, and the curves marked E in Diagram 3 show that no yield-point should be expected until a stress of $31\frac{1}{2}$ tons had been applied. The specimen was then kept for four hours at a temperature of from 670° to 690° C., and after cooling it was found that a stress of 26 tons per sq. inch caused considerable creeping to occur, and that with 27 tons per sq. inch a yield-point was certainly passed. After recovery from the overstrain caused by the application of the load of 27 tons per sq. inch, it was found that the yield-point had been raised to between 35 and 36 tons per sq. inch. By comparing these figures with those given in the table in the preceding page, it will be seen that annealing for four hours at about 680° C. has produced a slightly greater effect than was produced by annealing for a few minutes at 730° C.

* 'Phil. Trans.,' A, vol. 193, p. 34, 1899.

Experiments with Lowmoor Iron.

The Lowmoor iron, which was afterwards employed in order to show the phenomenon of tempering after hardening by tensile overstrain, was subjected to an examination exactly similar to that described above for steel. An iron rod $\frac{3}{8}$ths of an inch in diameter, and somewhat over 6 feet long, was employed, and specimens were tested without being previously turned. The analysis of this material was kindly supplied by Messrs. EDGAR ALLEN & Co., Limited, Sheffield, and is as follows:—

Carbon	0·12	per cent.
Silicon	0·149	,,
Sulphur	0·011	,,
Phosphorus	0·076	,,
Manganese	trace	,,
Iron (by difference)	99·644	,,
	100·000	

An ultimate strength of 23 tons per sq. inch was attained with an elongation, omitting all local extension, of $24\frac{1}{2}$ per cent. on a 4-inch length, or, allowing for the local elongation at the neck which formed just outside the measured length, say an ultimate elongation of 27 or 28 per cent. on the 4-inch length.

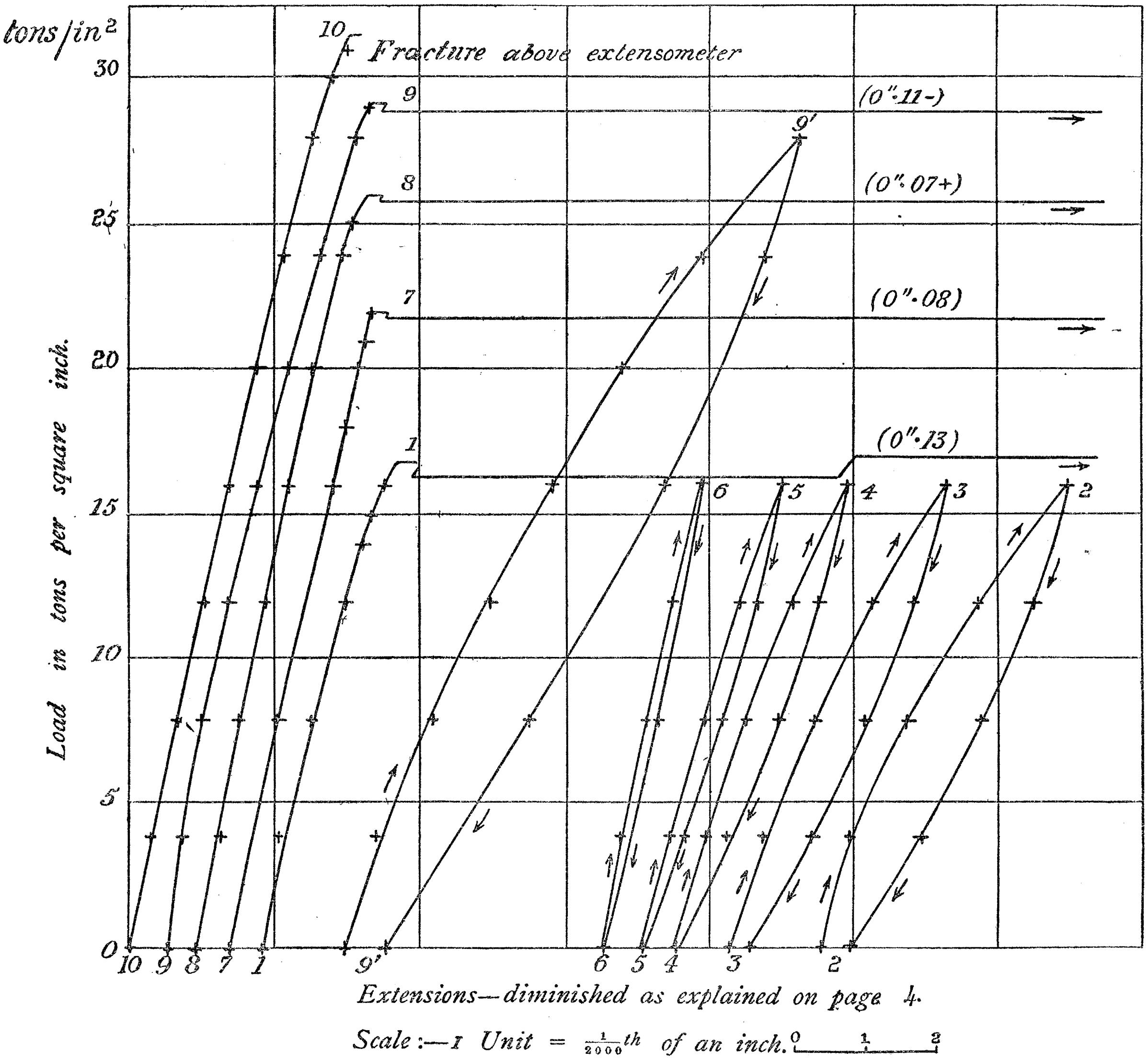
Diagram No. 4 shows the elastic properties of this material when tested in the condition as obtained from the makers. The primary yield-point is shown to have occurred at about 17 tons per sq. inch,* and the step by which the yield-point is raised after recovery from overstrain was about 4 tons per sq. inch. After the primary overstrain the yield-point was raised (when elasticity had been restored) by about $4\frac{1}{2}$ tons per sq. inch, after the second overstrain by 4 tons per sq. inch, after the third by less than $3\frac{1}{2}$ tons, while fracture occurred (outside the length under examination, however) $2\frac{1}{2}$ tons above the fourth yield-point. These figures seem to indicate a gradual and consistent diminution, as the load increases, of the step by which the yield-point is raised after recovery from overstrain. This is contrary to what was to be expected from the experiments with steel; but it may be remarked that Diagram 5, which gives the history of annealed specimens of the same Lowmoor iron, shows the step by which the yield-point is raised remaining practically constant.

Curves Nos. 2, 3, 4, 5, and 6 of Diagram 4 show the comparatively rapid rate at which Lowmoor iron recovers from tensile overstrain, the recovery only taking hours instead of days or weeks as in the case of steel. Curve No. 9 illustrates the

* Although 17 tons were applied before considerable yielding began, it was found that this yielding continued under a stress slightly over 16 tons/sq. inch, so that the yield-point should perhaps be placed at this latter stress.

semi-plastic nature of the material immediately after the fourth overstrain. All these curves were obtained from second loadings at the various times.

Diagram No. 4. (Lowmoor Iron as supplied.)



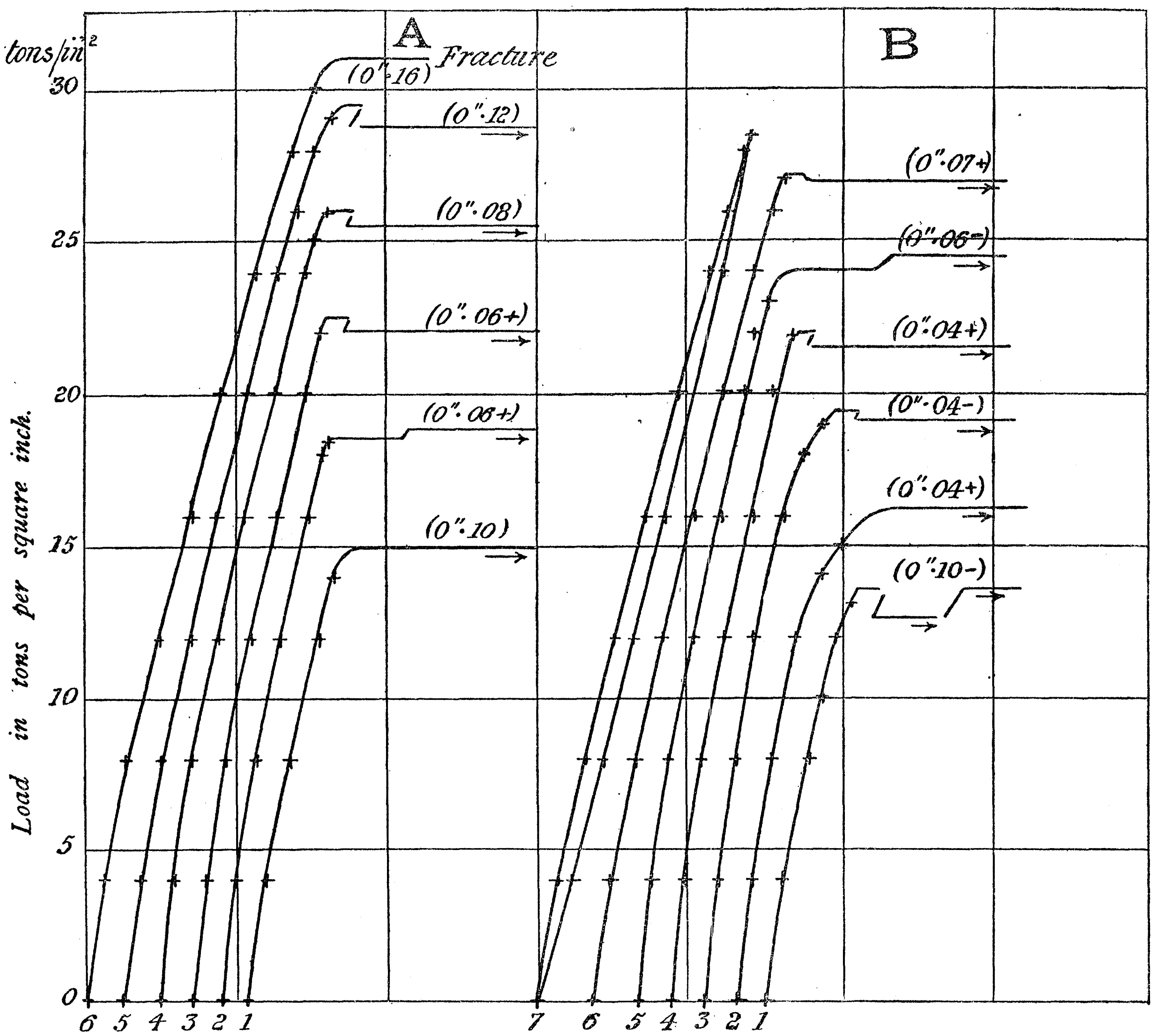
Curve No. 1—Primary test.	Curve No. 7—Immediately after No. 6.
" " 2—Shortly after No. 1.	" " 8—After heating to 150° C.
" " 3—½ hour " " 2.	" " 9— " " " 110° C.
" " 4—4 hours " " 2.	" " 9′—Shortly after No. 9.
" " 5—21 " " " 2.	" " 10—After heating to 140° C.
" " 6—After heating to 230° C.	

The first series of curves (A) in Diagram No. 5 gives the history of another specimen from the same bar of Lowmoor iron, but after the specimen had been heated to 770° C. and allowed to cool down in the air. The primary yield-point is shown to have been lowered from 17 to about 15 tons per sq. inch, and the step by which the

yield-point is raised after recovery from overstrain has been slightly diminished. Recovery from the various overstrains was effected by heating to about 150° C.

The series of curves marked B in Diagram 5 shows by comparison with the first series of curves in the diagram the influence of time on the effect of annealing. The specimens from which the two series of curves were obtained had both been heated

Diagram No. 5. (Annealed Lowmoor Iron.)



Extensions—diminished as explained on page 4.

Scale:—1 Unit = $\frac{1}{2000}$th of an inch. 0 1 2

A—Lowmoor Iron annealed for a few minutes at 770° C. and allowed to cool in air.

B— „ „ „ 6 hours at 750° C. and cooled very slowly.

to about the same temperature, but specimen A was simply raised to that temperature (770° C.) and then allowed to cool slowly in the air, while specimen B was kept at the temperature (about 750° C.. and never higher than 780° C.) for six

hours, and then very slowly cooled by gradually reducing the gas supply while the specimen was kept in the furnace. The effect of prolonged annealing is shown in the further lowering of the primary yield-point, in the diminution of the step by which the yield-point is raised, and in the reduction of the amount of stretch which occurs at a yield-point.

The Lowmoor iron, whose elastic properties have just been considered, was also examined by means of the microscope. A small piece was cut from each of the three specimens used to obtain the curves of Diagrams 4 and 5; these small pieces of material were polished, etched with dilute nitric acid (2 per cent. strength), and examined under a magnification of 100 diameters. Fig. 1 (Plate 1) shows the micro-structure of the material when in the condition as supplied by the makers. The granules were comparatively small, and slag was fairly uniformly distributed in small quantities all over the section. Fig. 2 (Plate 1) shows the structure of the iron which had been annealed at 750° C. for six hours, that is, this figure shows the structure of the specimen whose elastic properties are illustrated at B, Diagram 5. The granules are shown to be much larger than in the material in the condition as supplied; the slag had consequently segregated into larger masses.* The sections in figs. 1 and 2 were transverse to the length of the rod of iron. The photograph reproduced in fig. 1 was taken from a portion of the section where the granules were larger than the average, and where the slag was less thickly distributed. Fig. 2, on the other hand, shows by no means the largest granules found in the material after it had been annealed, but it should be stated that in some portions of the annealed material the granules were still found to be quite small.

The specimen taken from the bar used to obtain curves A of Diagram 5, that is, the specimen of Lowmoor iron which had been annealed by heating to 750° C. for only a few minutes, showed granules larger than in the virgin material, but, taking the average, distinctly smaller than those shown with the material which had been subjected to prolonged annealing. This is, of course, in accordance with ARNOLD's and STEAD's results. It should be remembered, however, that the structures of annealed specimens in particular were found to be by no means uniform, so that a complete survey of the sections had to be made in order to get a just comparison of the different granular structures.

To return to the elastic properties of the Lowmoor iron, attention may be called to the fact that the permanent sets which occurred at the various yield-points are marked in both series of curves in Diagram 5, and also at the yield-points in Diagram 4. The total elongation of the specimen of Diagram 4, owing to the position of the fracture, could not be exactly measured, but it was probably about 12 per cent. on a 4-inch length. The breaking load was $31\frac{1}{2}$ tons per sq. inch.

* This change in structure produced by annealing has been shown by ARNOLD, "On the Influence of Carbon on Iron," 'Proc. Inst. C.E.,' 1895; and by STEAD, "The Crystalline Structure of Iron and Steel," 'Journ. Iron and Steel Inst.,' 1898.

Specimen A of Diagram 5 gave an ultimate strength of 31 tons, with an elongation of $14\frac{1}{2}$ per cent. on 4 inches. The virgin material tested in the usual fashion, that is, without effecting recoveries from overstrain, broke at 23 tons, with an elongation of 27 or 28 per cent. on 4 inches.

Distinctions between various Hardnesses.

The examinations of both iron and steel which have been described above show that thin bars of material in the condition as supplied by the makers are more or less hard; abnormally high yield-points are exhibited, ultimate strengths are somewhat higher, and ultimate elongations somewhat lower than those obtained with material which has been annealed. This hardness is probably due to conditions of manufacture. The bars may leave the rolling mills at a comparatively low temperature (say not higher than 600° C.), and so be subjected, in passing through the rolls, to a species of overstraining at a moderately high temperature. The material may also be suddenly cooled through some range of temperature more or less high. It has been shown above (Diagram 3) that this hardness of thin rods of iron and steel, when in the condition as supplied by the makers, may be gradually reduced by the process of tempering or gradual annealing.

The hardness just referred to is not such as could be produced by simple tensile overstrain, that is, by giving the material a permanent stretch; nor is it such as is produced in steel by quenching in cold water. For, as compared with the properties of annealed material, the hardness of thin rods in the condition as supplied is characterised by a high primary yield-point, by the large amount of stretching which occurs at a yield-point, and by the large step through which the yield-point is raised after recovery from tensile overstrain. This is shown by the comparison of Diagrams 1 and 2, or of Diagrams 4 and 5. Material which has been hardened by simple stretching is characterised by a high primary yield-point, but by no change (as compared with the properties of annealed material) in the amount of yielding at the yield-point or in the step by which the yield-point is raised after recovery from tensile overstrain. Steel which has been hardened by quenching exhibits no distinct yield-point, and the structure of quenched steel, as revealed by the microscope, is entirely different in character from that of annealed steel.

The Tempering of Steel Hardened by Stretching.

Perhaps the simplest method of showing the tempering of steel hardened by stretching would have been to have taken a series of annealed specimens from the same rod of steel, to have hardened them all to the same extent by tensile overstrain, and then to have tried the effect of heating to various temperatures, a different temperature being used for each specimen, just as was done to obtain Diagram No. 3.

Instead of doing this, the extended series of experiments described below, and illustrated by Diagram 6, were performed on a single specimen, and the results obtained were corroborated by a few simple experiments, using other specimens. It was shown in this manner that a temperature as low as 300° C. could effect tempering or partial annealing, provided the material was sufficiently hardened by tensile overstrain. The harder the material was made, that is, the higher the yield-point was raised by the preliminary stretching, the lower was the temperature which could be shown to have a tempering or annealing action; and the higher the temperature employed, the greater was the tempering or annealing effect produced.

The material employed to obtain Diagram No. 6 (which shows the tempering of steel hardened by stretching) was the semi-mild steel whose analysis is given on a previous page, and whose elastic properties are illustrated by Diagrams 1 and 2. A specimen of this material was turned down (except at the ends) to a diameter of about 0·4 of an inch, and was then annealed by being heated to 820° C., and allowed to cool slowly. It was necessary to anneal the specimen, for otherwise the hardness produced by tensile overstrain would have been superposed on the hardness referred to above as having been produced in the process of manufacture. A 4-inch length was then marked off on the specimen by the aid of the marking instrument, the extensometer was attached, load was applied, and Curve No. 1 of Diagram 6 was plotted from the readings taken. The loading was continued until a yield-point was passed at 28 tons per sq. inch.

Recovery from this first overstrain was effected by heating the specimen to over 200° C., and allowing it to cool slowly. The specimen was then hardened still further by the two successive overstrains illustrated by Curves 2 and 3, Diagram 6.

After recovery from the third overstrain it was known that the material should bear a load about 7 tons higher than the last overstraining load (7 tons being the step between the yield-points shown by Curves 1, 2, and 3); that is, the material should bear a load of about 50 tons per sq. inch before a yield-point was passed. As, however, experience had shown that fracture was liable to occur when the material was stressed to this extent, no further hardening of the material was attempted.*

Curve No. 4, Diagram 6, is given in order to show that after recovery from the third overstrain (by heating to 270° C.) the material could bear a load of at least 48 tons per sq. inch without reaching a yield-point. As indicated above, probably a load just under 50 tons could have been safely applied. Slight imperfection of elasticity is shown by Curve No. 4, but this could not be got rid of by the ordinary means adopted to procure restoration of elasticity after overstrain. With this material there was always a slight departure from HOOKE'S law before a yield-point was

* Another specimen of the same rod, after annealing at 775° C., was found to give yield-points at about 29, 37, 44, and 52 tons per square inch; but after the yielding at the last stress had just spread throughout the 4-inch length under test, a neck formed and fracture occurred.

reached, and on the removal of a load less than that of the yield-point, a slight permanent set was often recorded. A second loading usually brought the material into a cyclic state, a hysteresis cycle such as that shown by this Curve No. 4 being obtained.

The specimen under consideration was now heated to 360° C., allowed to cool slowly and then tested. It was not expected that this temperature would have had any tempering or annealing effect, but Curve No. 5, Diagram 6, shows that the hardness of the material had been somewhat reduced, a yield-point being reached at 47 tons per sq. inch, that is, the position of the yield-point had been lowered by about 3 tons per sq. inch as a consequence of the heating at 360° C.

The test illustrated by Curve No. 5 involved of course a further hardening of the material, so to effect recovery from overstrain the specimen was heated to 310° C. The furnace had been kept hot, so the specimen was only in for about 15 minutes before the gas was turned off, and the furnace and specimen were allowed to cool down together. On testing the specimen it was found that 52 tons per sq. inch could now be safely applied, and as a yield-point would be expected rather under 54 tons (*i.e.*, 47+7) tons per sq. inch if only recovery of elasticity had been effected, it follows that very little if any annealing action had been produced by raising the material to 310° C. The specimen was again raised to 310° C. and kept at that temperature for 2 hours. Curve No. 6 shows that still there had been no appreciable tempering or annealing action. A temperature very little higher than this would probably have produced a measurable lowering of the yield-point, but in order to avoid danger of fracture the specimen was raised to 500° C., and Curve No. 7 shows the considerable lowering of the yield-point which resulted. At a load of 40 tons per sq. inch large yielding set in, and with 41 tons a yield-point was certainly passed.

The specimen was now first heated to 350° C., and no appreciable annealing effect was found to have been produced. A temperature of 380° C. was then tried, and still it was found that the specimen could withstand a load of 46 tons per sq. inch without yielding. In consequence of overstrain and recovery from overstrain a yield-point would be expected at 48 (*i.e.*, 41+7) tons per sq. inch. The specimen was then kept for one hour at a temperature from 380 to 390° C., cooled and tested with the same result as before. A temperature of 410° C. was then tried, and finally 430° C. was found to produce only very slight annealing, a yield-point occurring just under 46 tons per sq. inch. Curve No. 9, Diagram 6, illustrates this test.

The subsequent history of this specimen will be understood by reference to Diagram No. 6. The temperatures marked at the top of the various curves in the diagram are those to which the specimen had been raised immediately preceding the test from which the curve in question was obtained. The specimen was of course always tested at the temperature of the laboratory. The permanent exten-

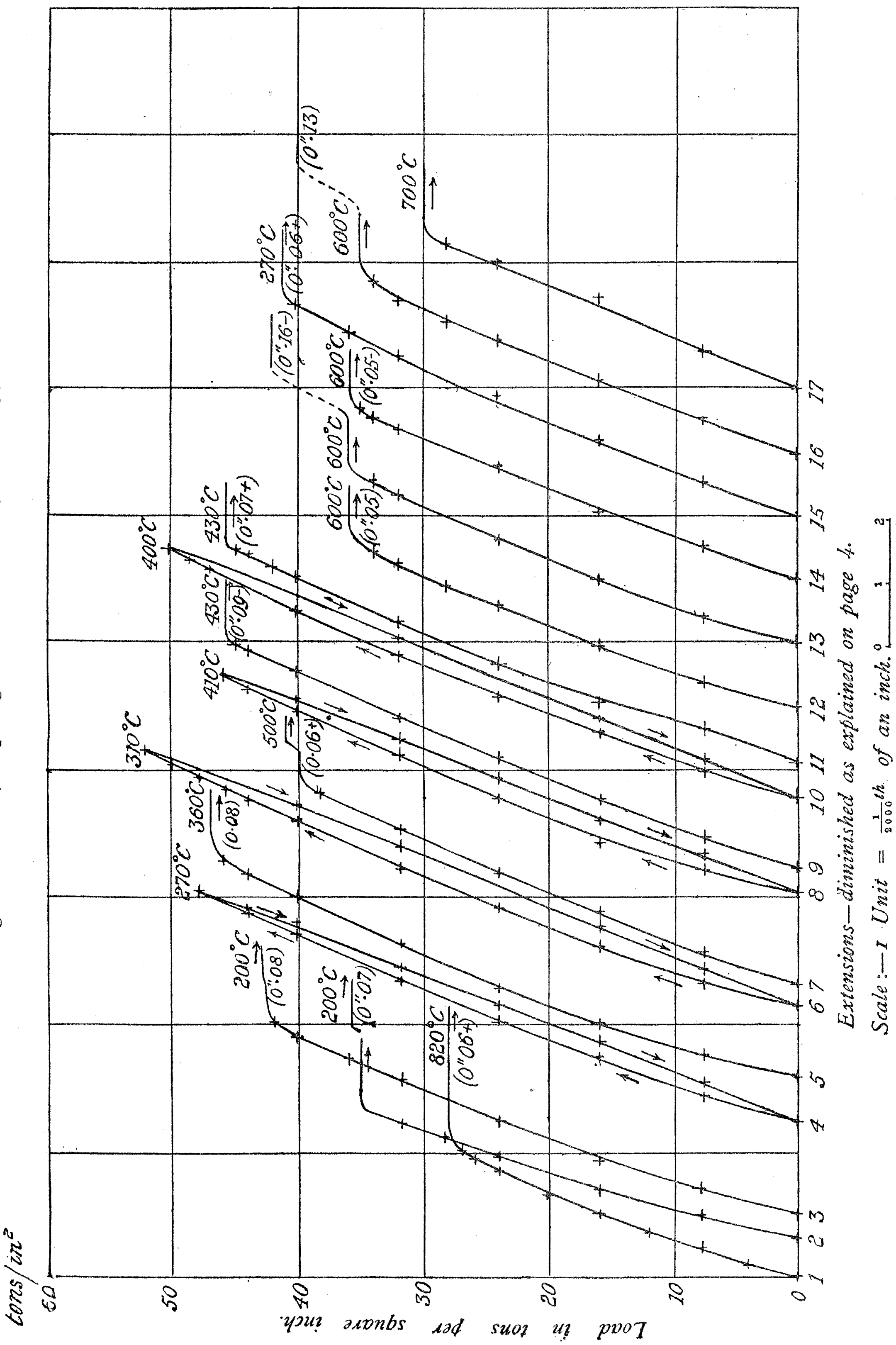


Diagram No. 6. (Tempering of Steel hardened by stretching.)

sions which occurred at the various yield-points are also marked (within brackets) below the yield-points. These extensions implied of course a diminution in the diameter of the specimen, this was allowed for in the loading, the loading being always in tons per sq. inch of actual section.

The tests illustrated by Curves 12, 13, 14, 15, and 16 were made in order to try whether the method or the amount of the overstrain given to the specimen altered the temperature required to produce a certain annealing effect. The experiments seemed to show that a definite annealing temperature corresponded to a definite position of the yield-point, no matter how or to what the extent the material had been overstrained.

After Curve No. 16 was obtained, the specimen was subjected to a treatment which practically resulted in a repetition of Curves Nos. 13, 14, and 15, the temperature of 600° C. being still employed, and finally the specimen was heated to 700° C., and Curve No. 17 obtained. The yield-point was now lowered to 30 tons per sq. inch, which is only 2 tons higher than the yield-point obtained when first testing this specimen after it had been annealed by heating to 820° C.

Experiments were made with another specimen of the same steel, and these served to corroborate the results which have just been described and which are illustrated by Diagram No. 6. It was thus shown that steel hardened by successive tensile overstrains may be softened to a greater or less degree by heating to temperatures ranging between 350° C. and 750 or 800° C.; and that the higher the temperature, the greater is the softening produced, or the lower is the stress to which the yield-point is brought.

In order to show tempering produced by comparatively low temperatures, it is necessary to severely overstrain the steel, so as to bring it into a condition having a large elastic range. In Diagram No. 6 the lowest temperature shown to have had a tempering or annealing effect is 360° C., but there is no doubt that a lower temperature than this could have been shown to have had a tempering action, had the specimen in the first place been more severely overstrained. That it was possible to further harden this material is shown by Diagram No. 2, where a fourth yield-point was safely passed, and the material brought into the condition having an elastic range of from zero to almost 59 tons per sq. inch, instead of only to 50 tons as in Diagram 6. If then, as shown by Diagram 6, a temperature of 360° C. sufficed to lower the yield-point to 47 tons per sq. inch when the elastic range was from zero to 50 tons, it seems probable that temperatures even under 300° C. would suffice to produce a slight tempering or annealing effect when the range of elasticity extended to 59 tons. It may be remarked, however, that the temperature of rather over 300° C. which was employed to effect the last restoration of elasticity illustrated in Diagram 2, is shown by Curve No. 8 of that diagram to have had very little if any annealing action. In this curve large yielding is shown to have started at 59 tons per sq. inch, and a yield-point would

have been expected at $59\frac{1}{2}$ tons had only restoration of elasticity been effected by the heating to slightly over 300° C. Another specimen of the same steel also showed that 350° C. was not sufficiently high a temperature to effect any softening of the material when it was in a condition having an elastic range to 52 tons per sq. inch. A temperature of about 300° C. may therefore be taken as the lowest which could be shown with the steel in question to produce tempering from the condition of hardness produced by tensile overstrain.

It is further shown, by a comparison of Curves 9 and 11 and of Curves 12 to 16 in Diagram 6, that a definite annealing temperature corresponds to a fairly definite position of the yield-point. This simple relation, however, is not shown to have held throughout all the experiments of Diagram 6. Curve No. 5 shows that 360° C. has sufficed to lower the yield-point to 47 tons per sq. inch, while in Curve No. 10 no yield-point is shown up to the stress of 51 tons, although the material had previously been heated to 400° C.

Further experiments were made to test how far a definite annealing temperature corresponded to a definite position of the yield-point. A specimen of the same steel as employed in the experiments described above was primarily annealed by being heated to 780° C., and slowly cooled, and was then overstrained by simply loading to the primary yield-point, which occurred at 29 tons per sq. inch. The specimen was then heated to 375° C., and after cooling loaded to 35 tons per sq. inch without a yield-point being passed. The yield-point, raised in consequence of recovery from overstrain, would have been expected at about 36 tons per sq. inch. The specimen was then heated successively to 400, 450, 500, and 550° C., and still the yield-point was found to be above 35 tons of stress. A temperature of 580° C. was next tried, and on testing the specimen after cooling, a yield-point was obtained at 33 tons per sq. inch. This result with a specimen which had been but slightly hardened by tensile overstrain, is practically in agreement with the results shown in Diagram 6, where after severe overstraining, and some tempering from the condition of hardness, a temperature of 600° C. is shown to have brought the yield-point to about 35 tons per sq. inch.

Another annealed specimen of the same steel rod was largely overstrained by carrying the primary loading far beyond the yield-point, which occurred at slightly over 28 tons per sq. inch. The load was steadily increased until a stress of 38 tons per sq. inch of original section was attained. This corresponded to a stress of about 40 tons on the actual reduced section of the bar. The extension produced by this loading was 0·22 of an inch on 4 inches of length. Recovery of elasticity was then effected by heating the specimen to 300° C. When cooled and tested, the specimen was found to bear a load of 44 tons per sq. inch without yielding. The specimen was then heated to 400° C., and after cooling, a load of 44 tons per sq. inch was again applied without a yield-point being passed. A temperature of 500° C. was next tried, and it was observed on testing the specimen that large yielding began

at the stress of 42 tons per sq. inch. A stress of $40\frac{1}{2}$ tons was, however, found sufficient to cause the yielding, once it had started, to spread throughout the length of the specimen. This result obtained with a specimen which had been largely overstrained by a single loading is, like the result of the experiment last described, in practical agreement with Diagram 6. Curve No. 7 of that diagram shows that, with a specimen which had been largely overstrained by the passage of several yield-points, a temperature of 500° C. brought the yield-point to a stress of 40 or 41 tons per sq. inch.

The Tempering of Lowmoor Iron Hardened by Stretching.

The tempering of Lowmoor iron which has been hardened by stretching now remains to be considered. A specimen of the soft iron whose properties were described in a preceding section of this paper, was annealed by heating to 750° C. with slow cooling, and was then subjected to the treatment illustrated by Diagram 6. The procedure adopted will be readily understood by reference to the diagram: it was practically identical with that adopted to obtain Diagram 6.

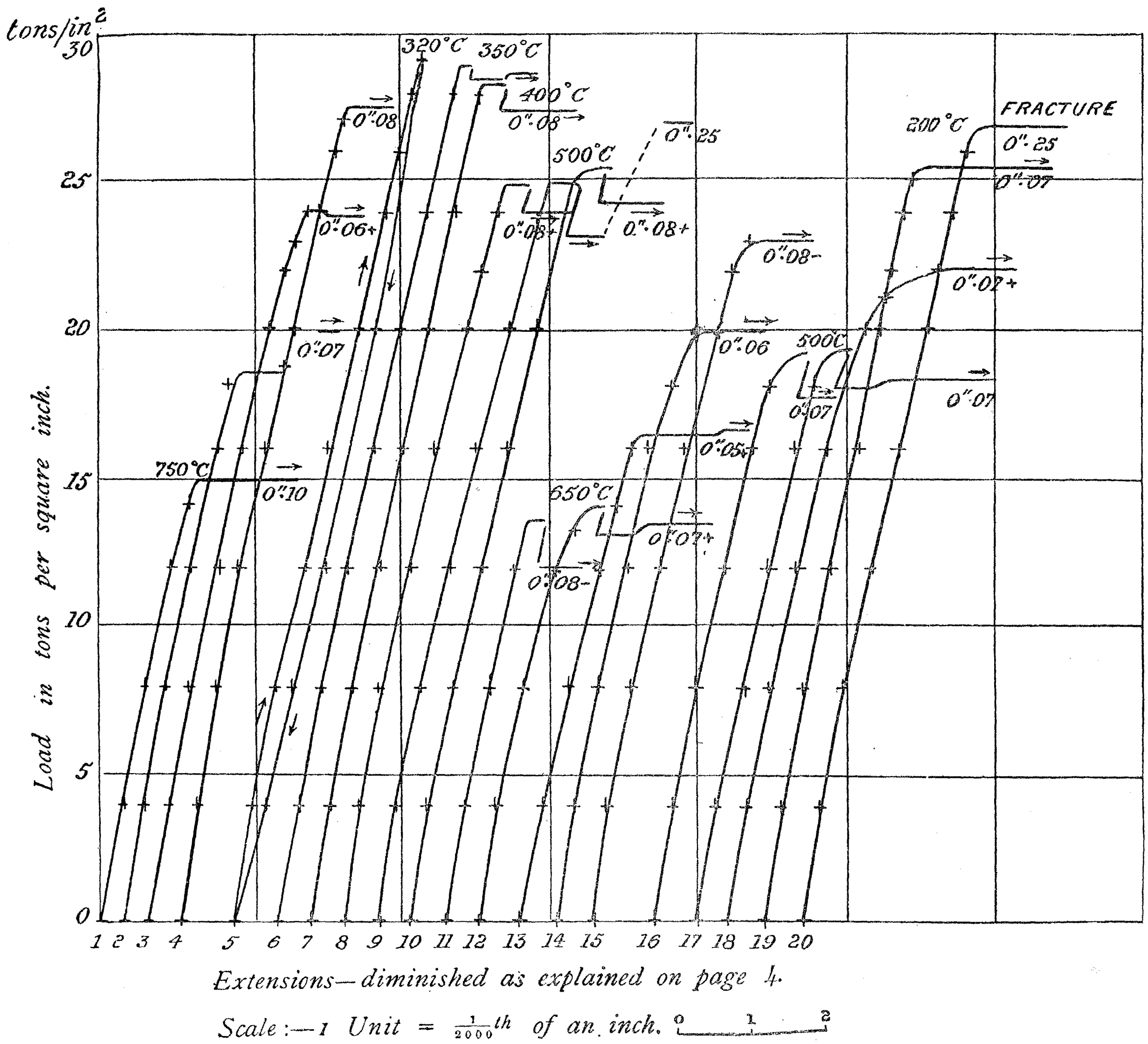
The specimen was first hardened by overstrain in the manner illustrated by Curves 1, 2, 3, and 4, Diagram 7. A temperature of 320° C. was then shown (Curve No. 5) to have had no tempering action on the hardened material, while the amount by which the yield-point was lowered in consequence of heating the specimen to 350 to 400 and to 500° C. is shown by Curves 6, 7 and 8 respectively.

Perhaps reference should again be made here to the method adopted to detect yield-points. The load was very slowly applied as its critical value was approached; the extensometer reading was continually observed in order to detect "creeping" within the 4-inch length under observation, and the lever of the testing machine was watched for any indication of yielding starting outside the measured length of the specimen. When "creeping" had been detected, the load was immediately reduced so as to keep the material yielding slowly. A considerable lowering of this load at the yield-point could often be effected, as is shown by the dip in various curves of the present Diagram No. 7, without causing the extension of the yield-point to stop; but since the rate of extension fluctuated somewhat as the stretching action travelled along, the load had sometimes to be slightly increased again in order to get the yielding to spread at a reasonable rate throughout the whole length of the specimen. The exact position of a yield-point is thus a little indefinite. By slightly reducing the load as the yielding at a yield-point was occurring, the danger of fracture supervening at the higher yield-points was somewhat reduced.

After curve No. 8 of Diagram 7 had been obtained, the specimen was again heated to 500° C., and Curve No. 9 shows that the yield-point had been brought to very much the same position as before. The loading in this test was carried far beyond the yield-point, and then the specimen was once more raised to 500° C. Curve No. 10

shows that the material now gave a yield-point at a stress only slightly higher than before.

Diagram No. 7. (Tempering of Lowmoor Iron hardened by stretching.)



A temperature of 650° C. was next tried, and it was found that this temperature lowered the yield-point by a remarkably large amount, Curves Nos. 11 and 12 showing that the material yielded at a stress distinctly less than that required to produce yielding in the very first test of this specimen, which it may be recalled had been annealed by heating to 750° C. Curves 11 and 12 thus show that the overstraining and tempering which the specimen received as the result of the operations illustrated by Curves 1 to 10 had brought the material into a condition more sensitive to the influence of temperature.

The material was now hardened again by successive overstrain in the manner illustrated by Curves 13, 14 and 15, Diagram 7, recovery from overstrain being

effected by warming to between 100 and 200° C., and then the specimen was heated to 500° C. to see if the yield-point would thus be brought to approximately the same position as in Curves 8, 9, and 10, which were obtained after the specimen was previously heated to this temperature. Curves Nos. 16 and 17 show that the yield-point occurred at a much lower stress than in the Curves 8, 9, and 10, so that the material was in an entirely changed condition as regards the effects of temperature.

A further hardening of the material was next attempted, but fracture inadvertently occurred, as illustrated by Curve No. 20. A temperature of 200° C. had been employed to effect recovery from the overstrain illustrated by Curve 19, but Curve No. 20 seems to indicate that this temperature had been sufficient to produce annealing action, because large yielding and then fracture occurred at a load distinctly lower than would naturally have been expected. This test was perhaps not quite conclusive as showing tempering by 200° C., for the specimen after so many overstrains was not very uniform in section, and the fracture occurred at what was known to be a rather thick part of the bar. It is thus just possible that the fracture was due to the bar not having been thoroughly overstrained by the preceding loading, although in that case yielding might have been expected to have started below 26 tons per square inch instead of at 27 tons per square inch. On measuring the fractured specimen it was found that the length, which had been originally 4 inches long, was now 5·80 inches.

Had fracture not inadvertently occurred, as explained above, there seems to be no reason why this specimen should not have been overstrained and tempered or annealed an indefinite number of times, and so the material have become drawn out into the form of a wire.

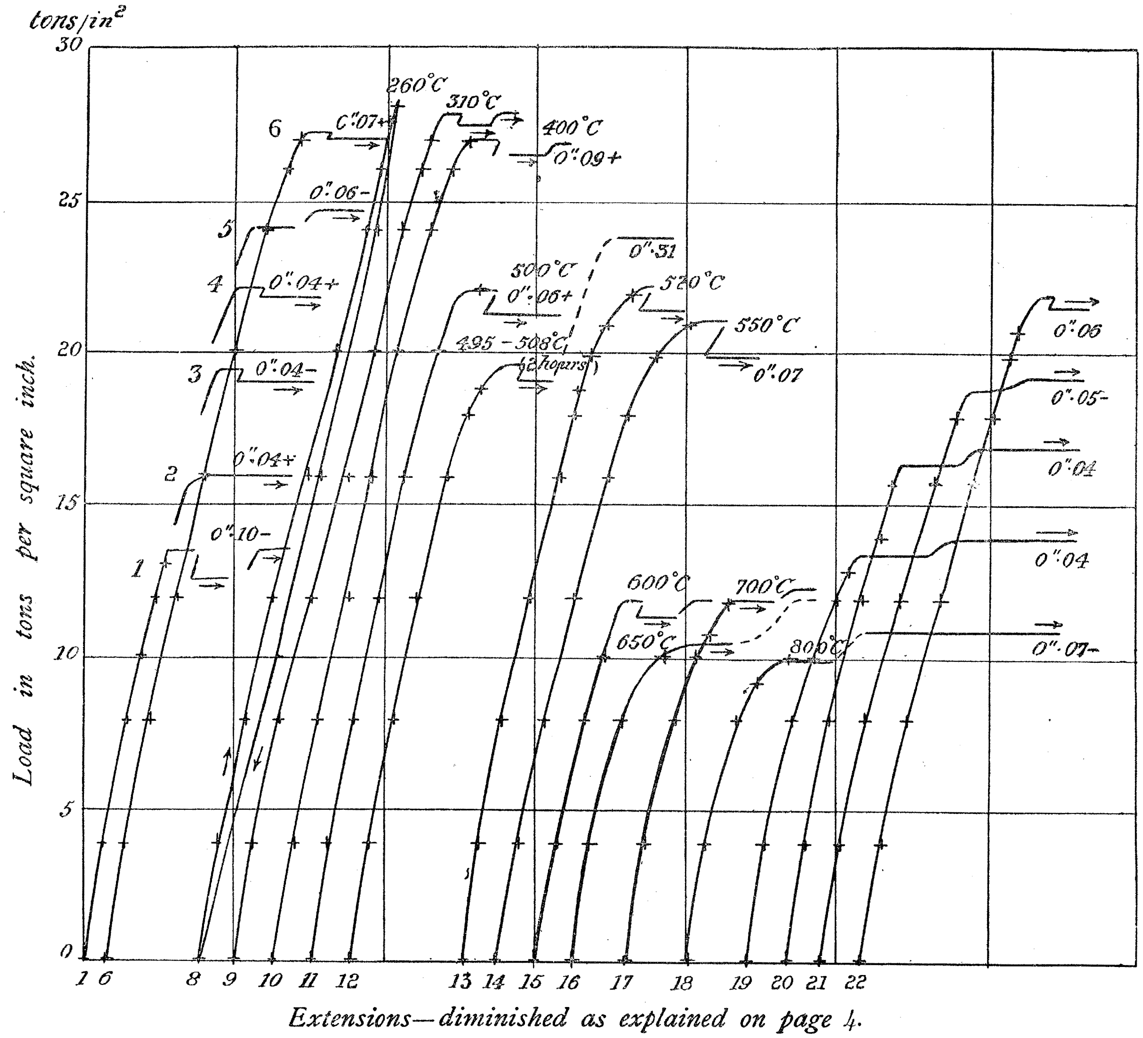
The history of another specimen of the same Lowmoor iron is given in Diagram No. 8, and the results recorded in that diagram serve generally to corroborate those illustrated by Diagram 7. The specimen employed has already been referred to in the preliminary examination of the Lowmoor iron described above. It was the specimen which was subjected to prolonged annealing at 750° C., and then hardened in the manner illustrated by the curves marked B in Diagram No. 5. In Diagram No. 8 there are illustrated the first and last overstrains in this hardening of the specimen, and also the position of the four intermediate yield-points.

Curve 8, Diagram 8, shows that 260° C. was too low a temperature to produce annealing, while Curve 9 shows that 310° C. sufficed to lower the yield-point by almost 2 tons per square inch. It is just possible that in the preliminary hardening of this specimen a seventh yield-point at a stress of about 29 tons per square inch might have been safely passed, and so the material after restoration of elasticity brought into a condition capable of bearing a load of 31 tons. Had this been safely accomplished, then no doubt a temperature lower than 310° C. would have sufficed to produce a tempering of the material.

A comparison of Curves 11 and 12, Diagram 8, indicates that time has some

influence on the tempering of Lowmoor iron hardened by overstrain. Curve No. 11 shows that 500° C. had lowered the yield-point to 21 or $21\frac{1}{2}$ tons per square inch, while Curve 12 shows that, by keeping the specimen for two hours at about 500° C., the yield-point was lowered to 19 tons per square inch. Time has no doubt a slight effect on the similar tempering of steel; but in both cases temperature is distinctly the main determining cause.

Diagram No. 8. (Tempering of Lowmoor Iron hardened by stretching.)



Scale:—1 Unit = $\frac{1}{2000}$th of an inch. 0 1 2

Curve No. 15, Diagram 8, which was obtained after heating to 600° C, shows a very large drop in the yield-point similar to the drop obtained at 650° C. with the specimen whose history is given in Diagram 7. The yield-point shown by Curve 15 is lower than that shown by Curve 1 of Diagram 8, that is, it is lower than the yield-point given with material which had been annealed for a long time at 750° C., but which had never been subjected to any tensile overstrain.

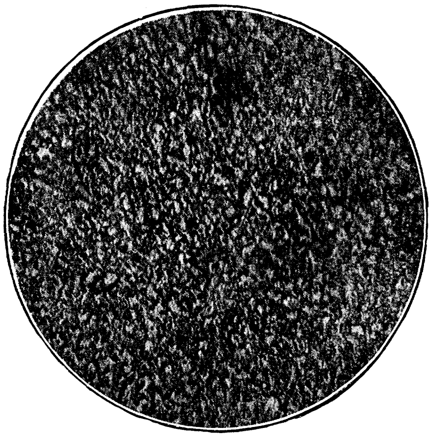


Fig. A—½″ Steel as supplied. × 150 D.
(Etched with HNO_3.)

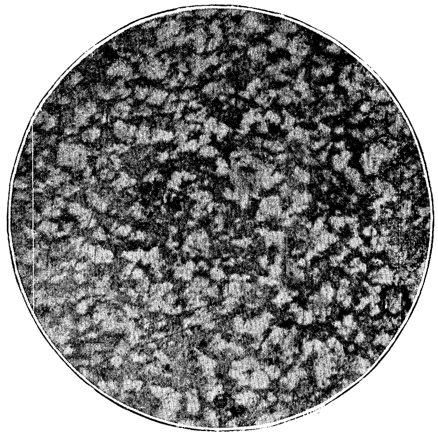


Fig. B—½″ Steel annealed for a few minutes at 750° C. × 150 D.
(Etched with HNO_3.)

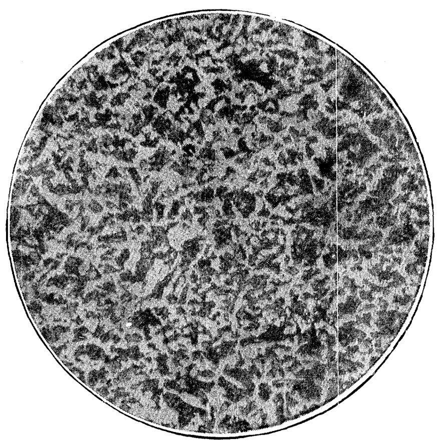


Fig. C—1″ Steel as supplied. × 150 D.
(Stained with Cocoa.)

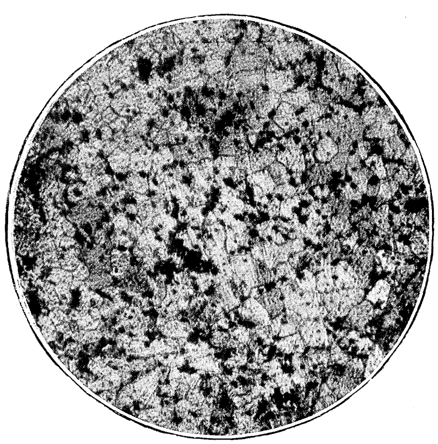


Fig. 1—Lowmoor Iron as supplied. × 100 D.
(Etched with HNO_3.)

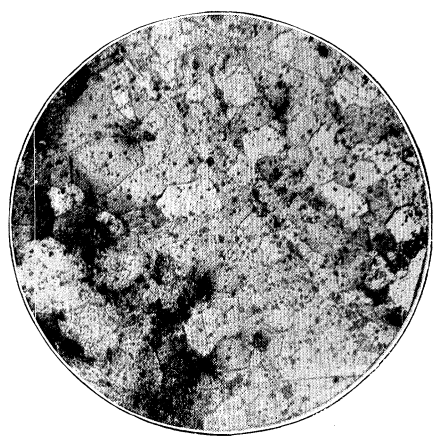
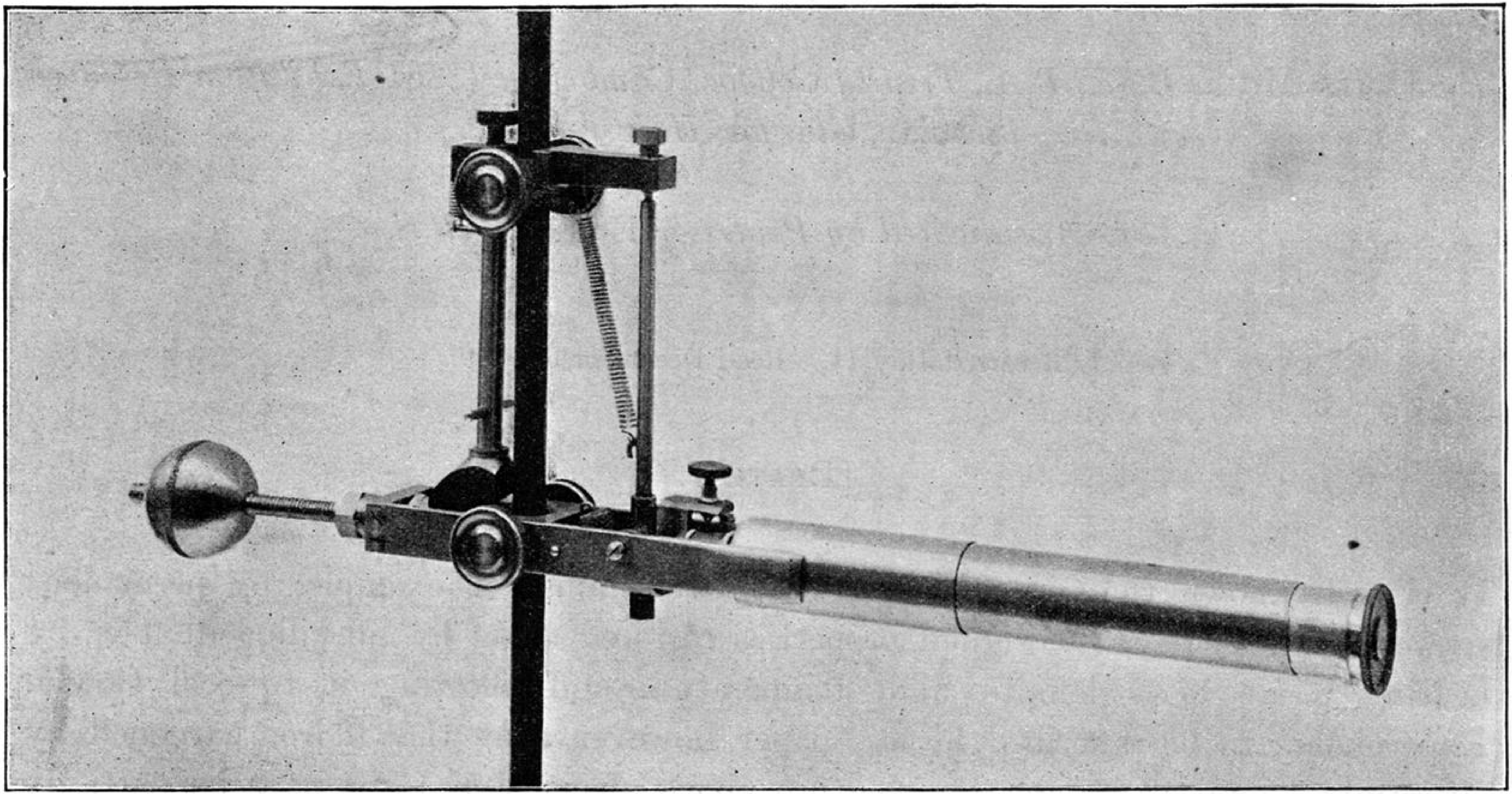


Fig. 2—Lowmoor Iron annealed for 6 hours at 750° C. × 100 D.
(Etched with HNO_3.)

The specimen whose history is given by Diagram 8 was ultimately heated to 800° C., and Curve 18 was obtained. The successive overstrains illustrated by Curves 19, 20, 21, and 22 were then applied, and the material was left in a condition of hardness, the tempering from which could be made the subject of further investigation.

In conclusion, it may be stated that many experiments other than those described above were performed during the course of this research. The preliminary experiments, which showed qualitatively the tempering of iron hardened by tensile overstrain, were performed in the Engineering Laboratory of the University of Glasgow, Professor BARR having kindly placed his laboratory and all necessary apparatus at the author's disposal. All the experiments described in this paper were carried out in the Engineering Laboratory of the University of Cambridge, and the author desires to express his indebtedness to Professor EWING for suggestions and advice given from time to time as the work was in progress.



4-inch Extensometer.

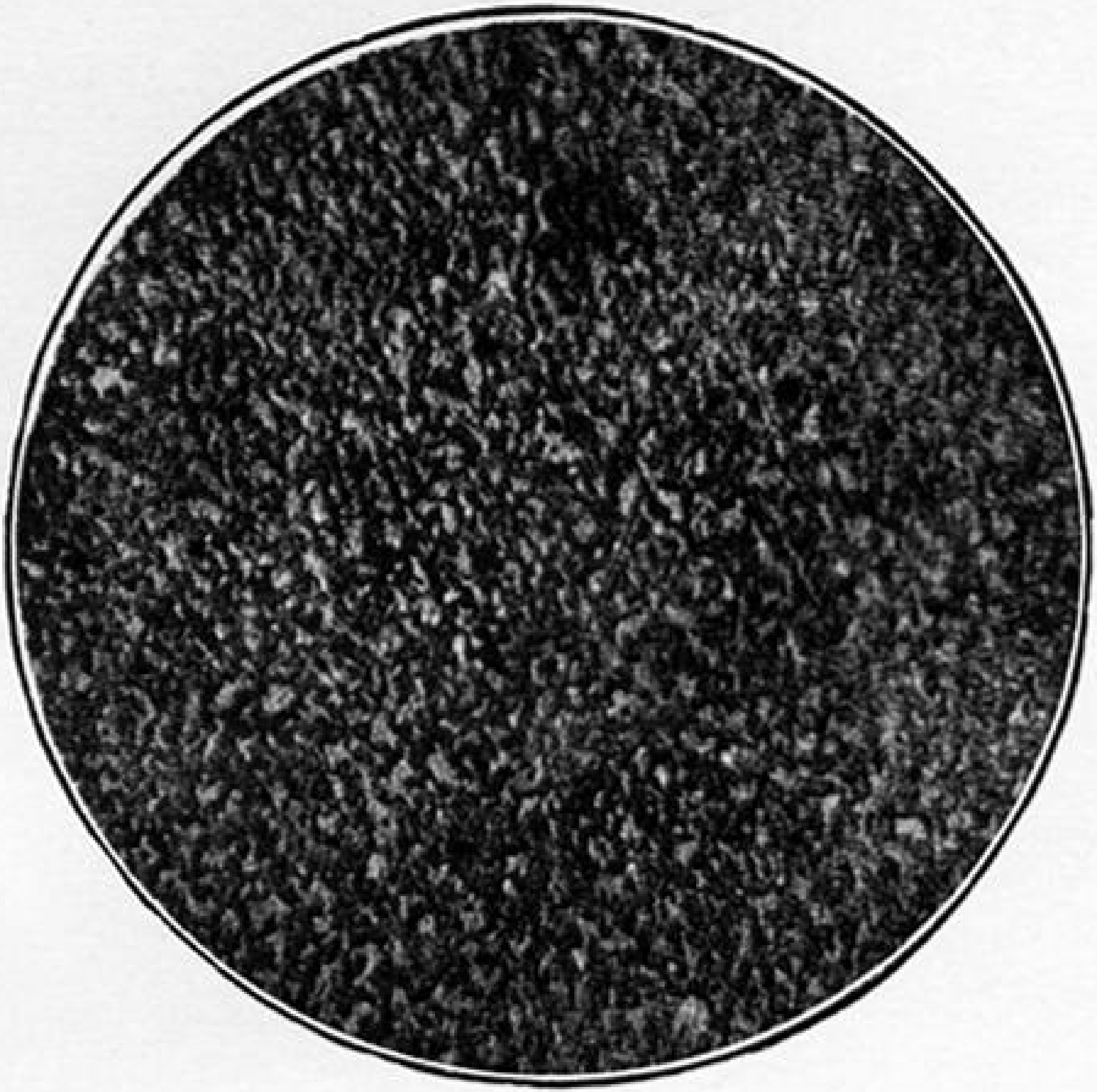


Fig. A—½″ Steel as supplied. × 150 D.
(Etched with HNO_3.)

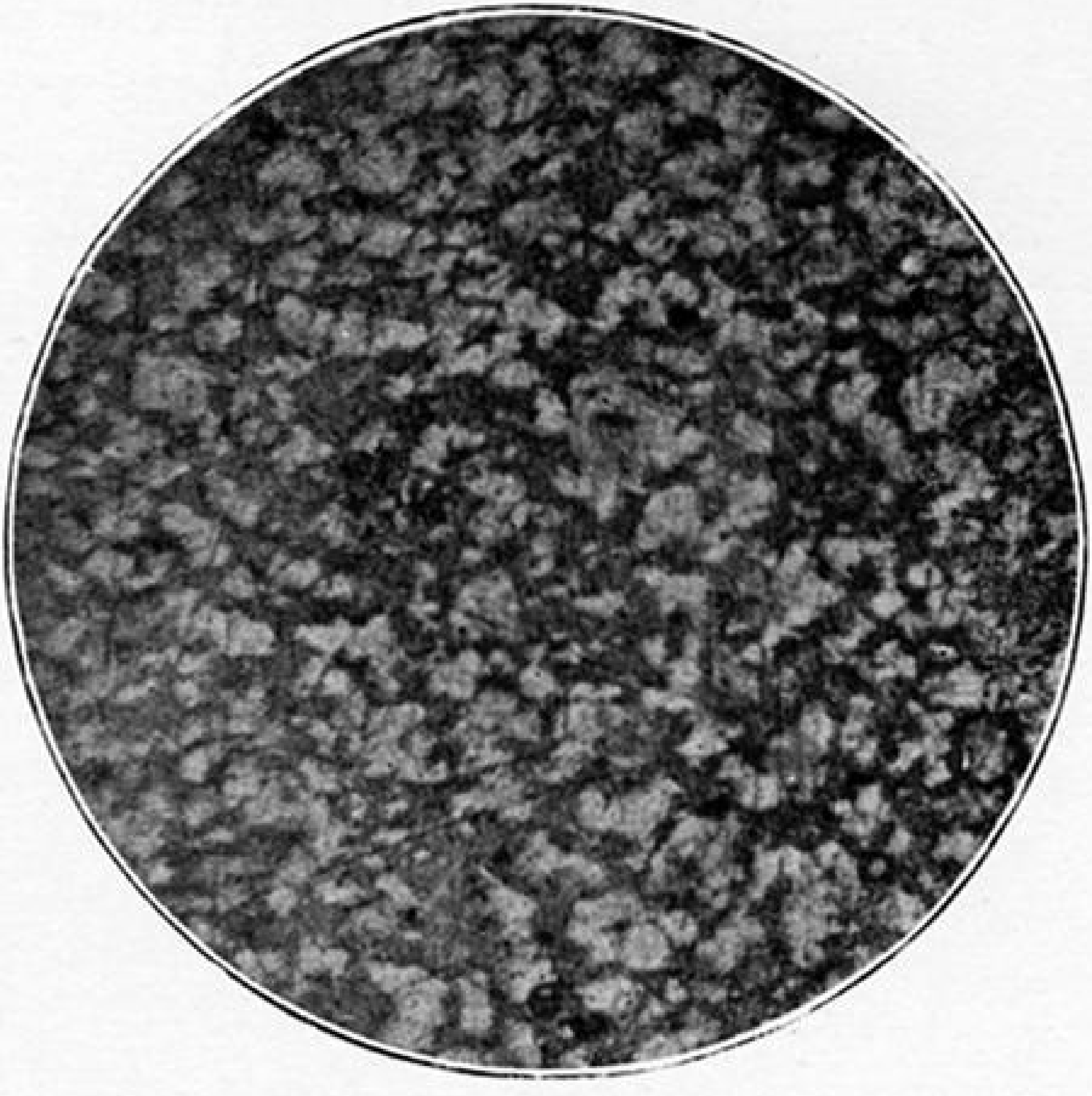


Fig. B—½″ Steel annealed for a few minutes at 750° C. × 150 D.
(Etched with HNO_3.)

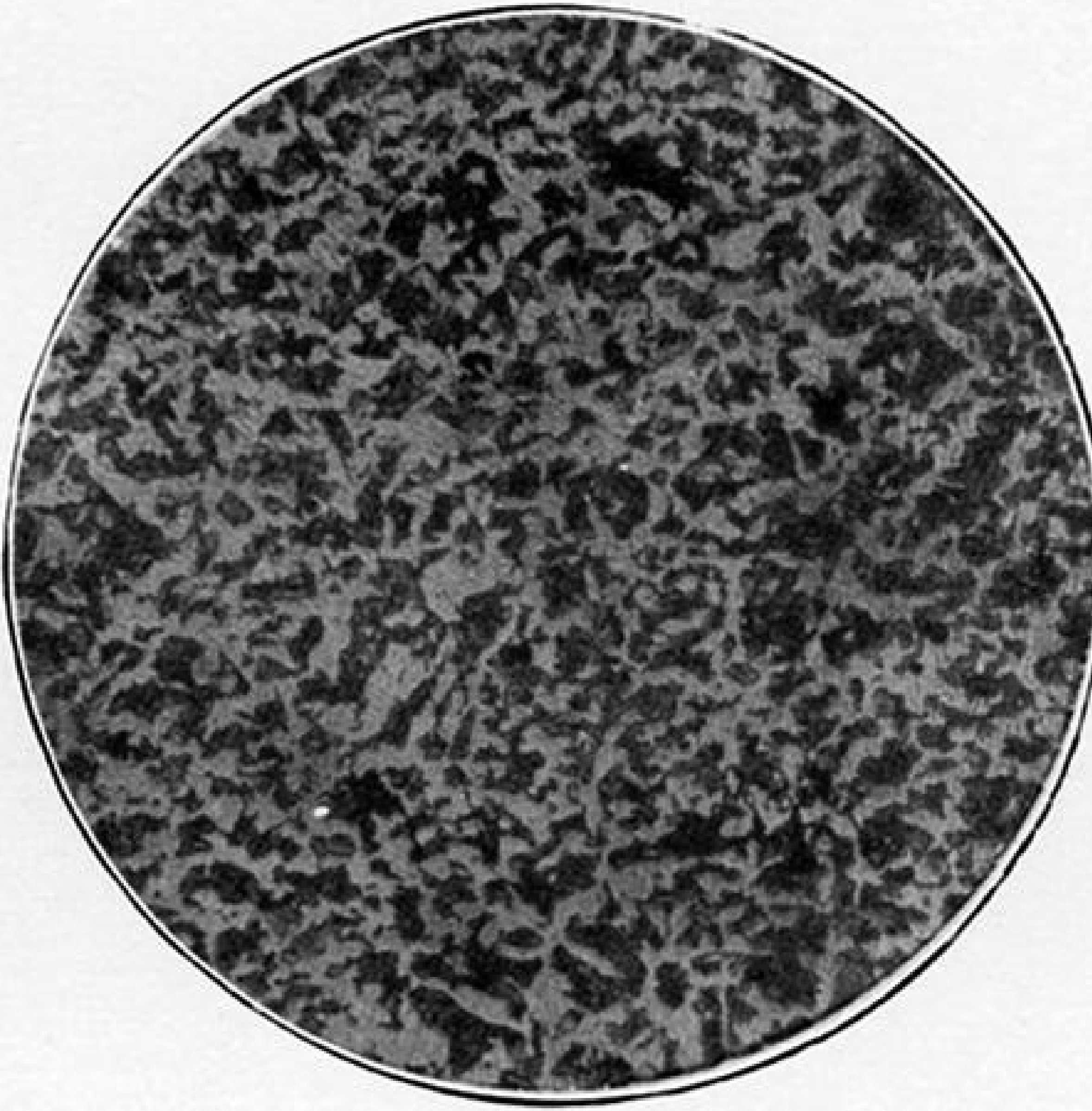


Fig. C—1″ Steel as supplied. × 150 D.
(Stained with Cocoa.)

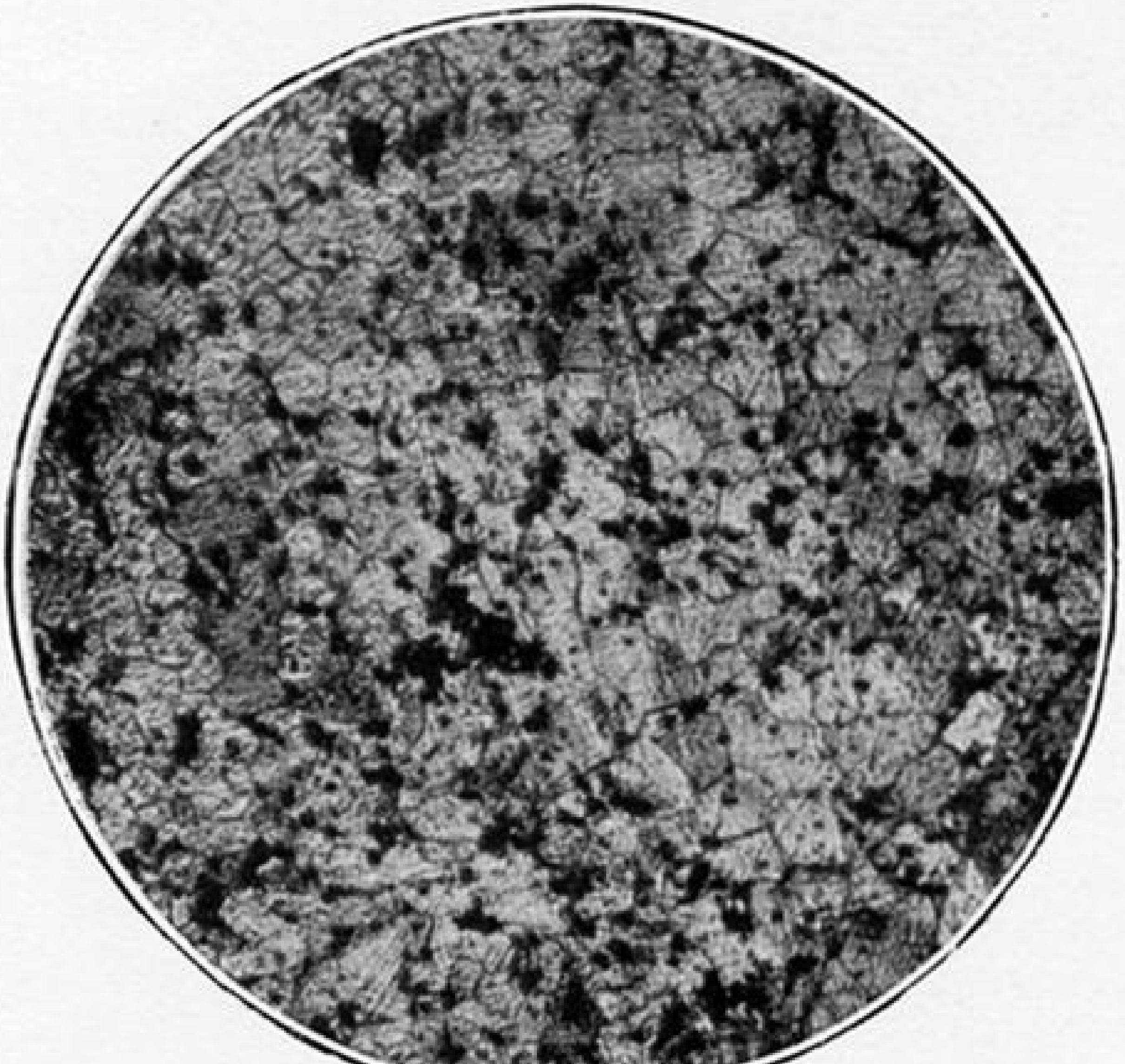


Fig. 1—Lowmoor Iron as supplied. × 100 D.
(Etched with HNO_3.)

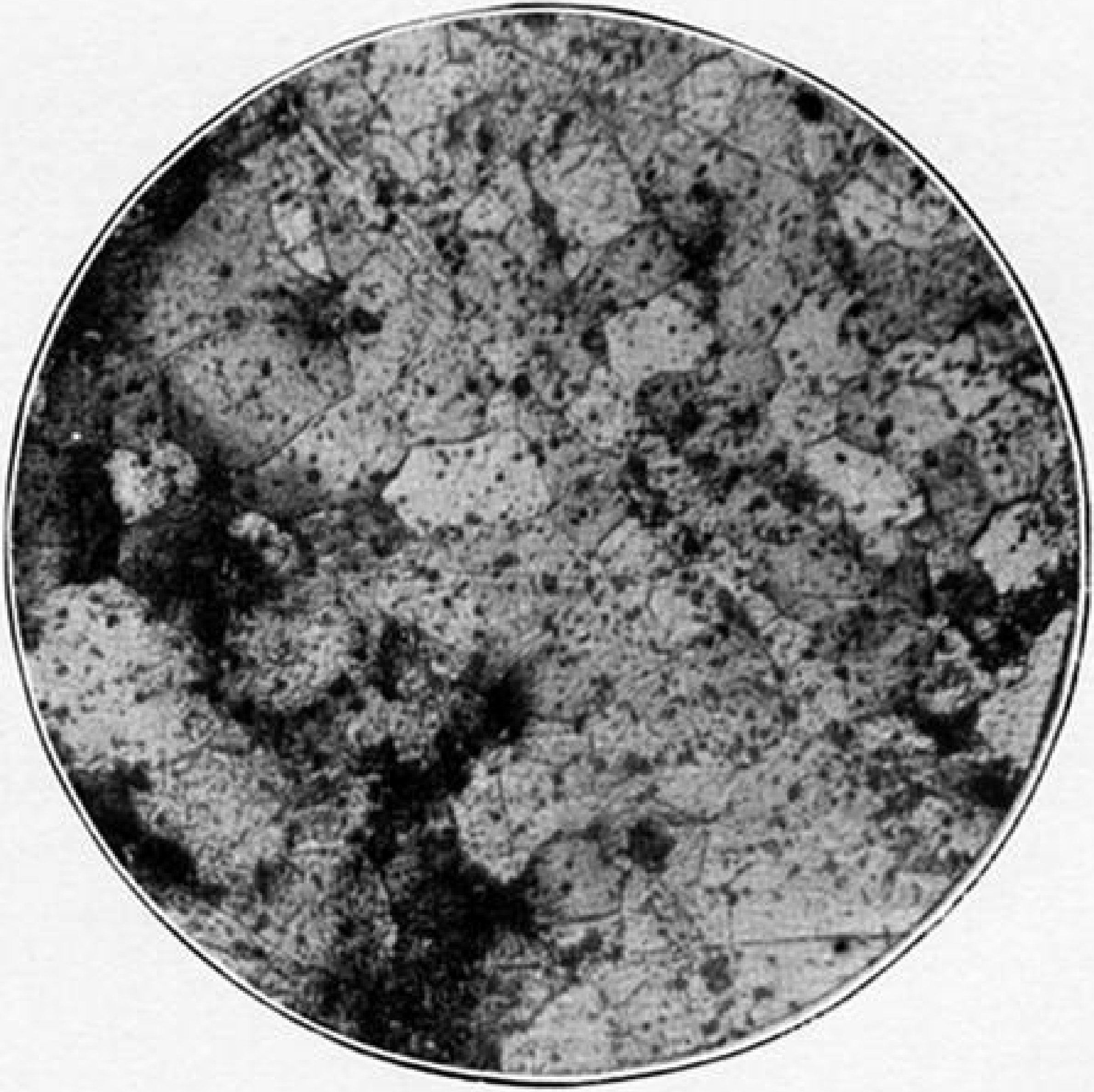


Fig. 2—Lowmoor Iron annealed for 6 hours at 750° C. × 100 D. (Etched with HNO_3.)