

appearances to which we are accustomed are inverted: it is the ferrite which shows black, and the pearlite light. In photographs taken from objects illuminated by vertical light, it is, on the contrary, the ferrite which is white. Returning to fig. 151, the envelopes of ferrite and their ramifications are easily seen: these envelopes are divided by

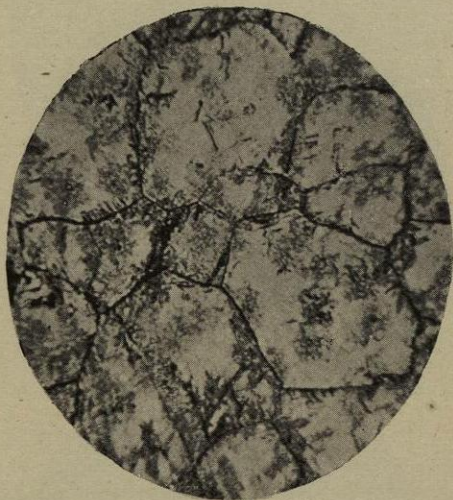


Fig. 152.—CARBON 0.45 per cent. Reheated to 1390° C.
Oblique illumination. $\times 20$ diameters.

an axial line, which is perhaps not sufficiently clear in the reproduction. These are the lines of contact which sometimes open into regular fissures, where the introduction of oxidising gases at high temperatures may form a layer of slag when this state is obtained. Burnt steel cannot be restored by any heat treatment, and always keeps its brittleness.¹

¹ Recent observations have, however, shown that the statements in this paragraph are susceptible of another explanation (see Appendix).—J. E. S.

There are no metals upon which the temperature of heating records itself more clearly than on steels of medium carbon content.

C. Influence of Quenching.—

(a) *Heating to variable temperatures, followed by quenching from the same temperature in water at 15°.*

This series of experiments will allow us to follow the diffusion of the carbon during the heating.

One plate was heated and quenched at 730°. Polishing in bas-relief isolates a large broken-up network of ferrite. Polish-attack shows, round this ferrite, a more or less wide border of troostite, coloured brown with blue spots (figs. 153, $V \times 100$; 132, $V \times 1000$). The rest is martensite, but, in the preparation photographed at 1000 diameters, the resolution of this last constituent has purposely not been pushed very far, in order that the troostite might be better distinguished.

The distribution of martensite and troostite is very irregular. Fig. 154 ($V \times 100$) shows another region where the troostite is much more abundant than in fig. 153. We see that at about 20° above the inverse point of recalescence the carbon was not yet diffused throughout the whole mass of the steel. At 1000°, on the contrary, the diffusion of carbon is practically complete.

Steel quenched at this temperature takes almost throughout a nearly specular polish on rouged parchment. The whole mass is in the state of martensite, except in certain places where, in the neighbourhood

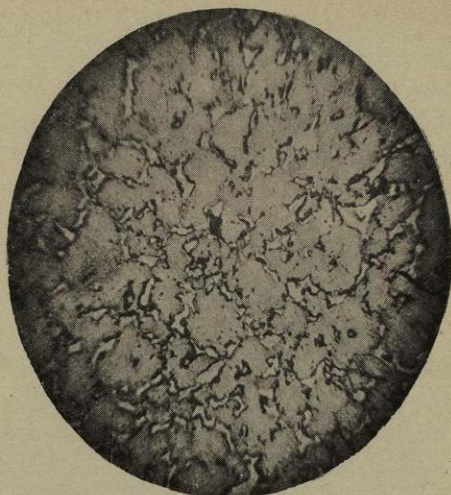


Fig. 153.—CARBON 0.45 per cent. Reheated and quenched from 730° C. Polish-attack. $V \times 100$ diameters. See also fig. 132.

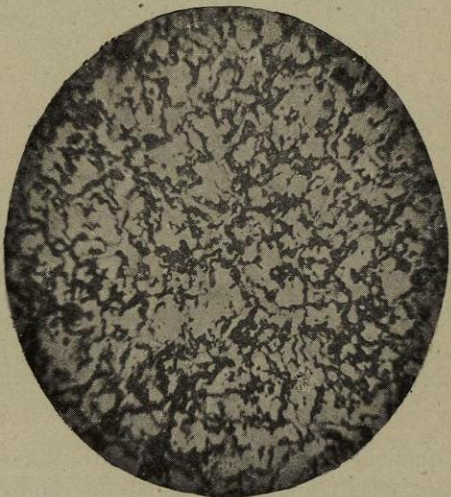


Fig. 154.—CARBON 0.45 per cent. Reheated and quenched from 770° C. Polish-attack. Shows more troostite than fig. 153. $V \times 100$ diameters.

of a slag inclusion, remains of troostite are found, together with traces of ferrite. The needles of martensite are longer and more regularly grouped than in the sample quenched at 730°. The boundaries of the crystalline groupings, besides being generally much confused, correspond to the places of minimum compactness, which nitric acid etches black by a deeper attack, and which may be transformed into actual cracks. The cracks, microscopic or not, may also follow the direction of the needles. There exists, then, in quenched steel a regular network of surfaces of weakness: this network must be the result of the correspondence of maximum tension, during the rapid contraction, with the planes of minimum resistance revealed by the actual structure. It is clearly enough shown by placing the polished specimen under a layer of water a few millimetres deep, and allowing one, two, or three drops successively of concentrated nitric acid to drop upon it through the water—a process of attack used by Werth, which certainly prevents the solution of the hardening carbon. The polyhedric elements appear to approximate to a pentagonal dodecahedron, like the grains of soft annealed steels. These are the grains of quenched steel: rudimentary when the temperature of quenching has been just sufficient, but which, in proportion as this temperature is raised, become larger and larger and more and more distinct. It is these grains which appear in the fracture.

A third sample was heated and quenched at 1225°. The diffusion of carbon is naturally more complete than it was in that quenched at 1000°. Martensite was then the only constituent, but the crystallites are better and more clearly developed. Their needles are

easily resolved by polish-attack (fig. 155, $V \times 800$). A beautiful wavy appearance is also obtained in an oblique light with small magnification (fig. 156, $V \times 20$). This preparation readily lends itself to the study of the origin of the grain which has been described above. All the varieties of surface weaknesses can be found there:—1st, the crack visible to

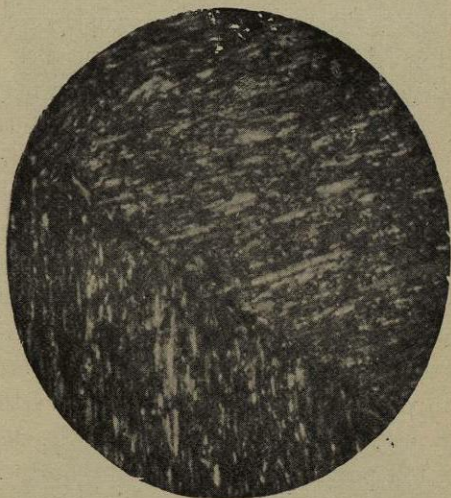


Fig. 155.—CARBON 0.45 per cent. Reheated to, and quenched from, 1225° C. Polish-attack and nitric acid. $V \times 800$ diameters.

the naked eye (fig. 157, $V \times 20$: polish-attack); 2nd, the line of least resistance at the common edge of two crystalline developments (fig. 155, already described); 3rd, the line of least compactness or of greatest tension, which, in crossing a crystalline region following a different direction from that of natural cleavages, shows its presence by a deeper attack of a certain width between the isolated needles (fig. 158, $V \times 800$: attack by iodine). Finally, fig. 159 ($V \times 100$: also



Fig. 156.—CARBON 0.45 per cent. Reheated to, and quenched from, 1225° C. Polish-attack and nitric acid. Oblique illumination. $\times 20$ diameters.

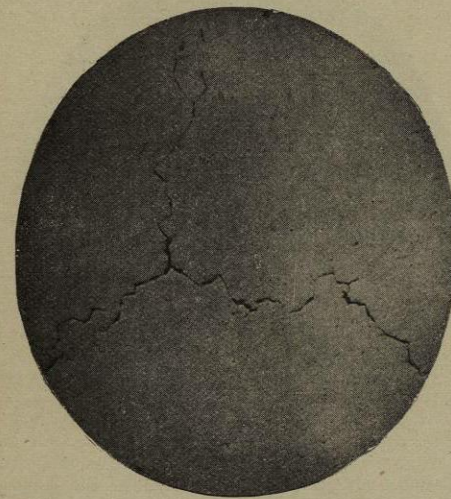


Fig. 157.—CARBON 0.45 per cent. Reheated to, and quenched from, 1225° C. Polish-attack. $V \times 20$ diameters.

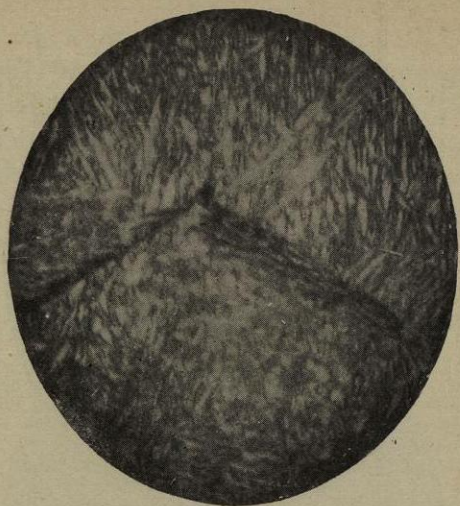


Fig. 158.—CARBON 0.45 per cent. Reheated to, and quenched from, 1225° C. Etched by tincture of iodine. ¹O × 800 diameters.

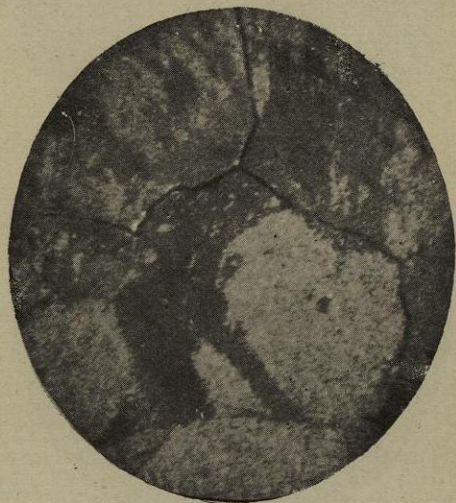
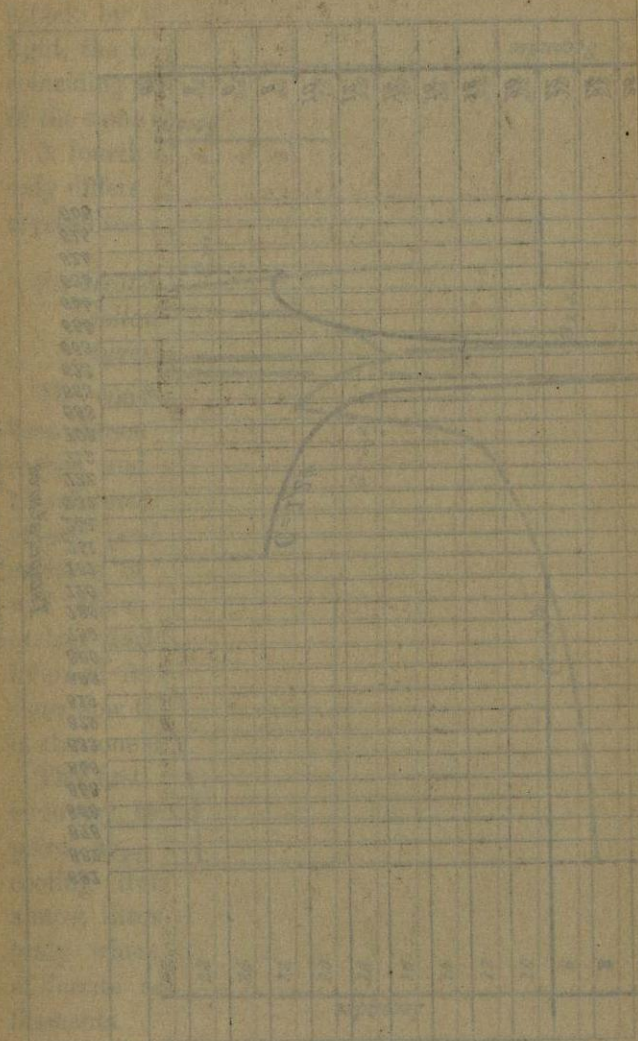
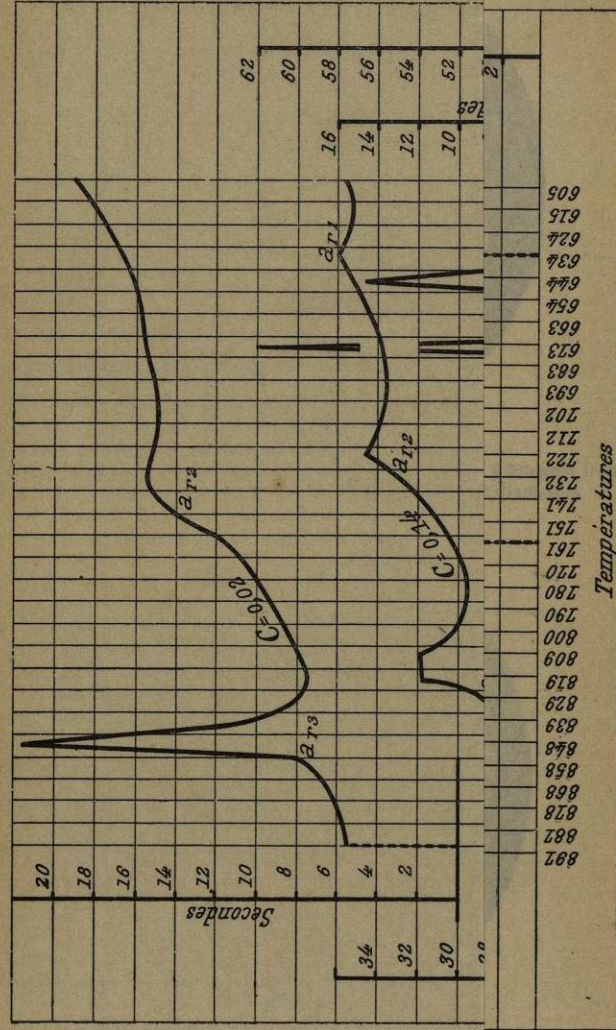


Fig. 159.—CARBON 0.45 per cent. Reheated to, and quenched from, 1225° C. Etched with tincture of iodine. O × 100 diameters.

¹ O means oblique illumination ; V, vertical.





Critical Points of Steel.

attack by iodine) allows one to trace, with oblique light, the course of a fissure usually, but not always, coinciding with the borders of the crystalline portions of the same orientation.

A fourth sample, heated and quenched at 1325°, only differs from the preceding by a new growth of crystallites, and demands no special attention.

(b) Heating at a constant temperature (845°), followed by quenching from variable temperatures in water at 15°.

The constant temperature of heating—825°—has been chosen so as to obtain the complete diffusion of carbon and the perfect accomplishment of all the transformations, whilst avoiding to the greatest extent possible the formation of a network of surfaces of weakness. This series of experiments will allow us to follow the concentration of the carbon during the cooling, as we have just now followed its dissemination during the heating, and to show how this concentration takes place here entirely in the zone of the critical points.

The first disc has been quenched at 720°—that is to say, before the beginning of the double critical point Ar_{3.2} (see curve, Plate I.)—and after a slow cooling from 825° to 720°. Polish-attack gives, almost throughout, martensite, and, in some regions (only where less carbon was present), a residue of ferrite accompanied by troostite occasionally in filaments.

A second sample was quenched at 690°, towards the maximum of Ar_{3.2}. The ferrite has become more abundant, and polish in bas-relief shows it in very numerous strips, which, however, do not yet join

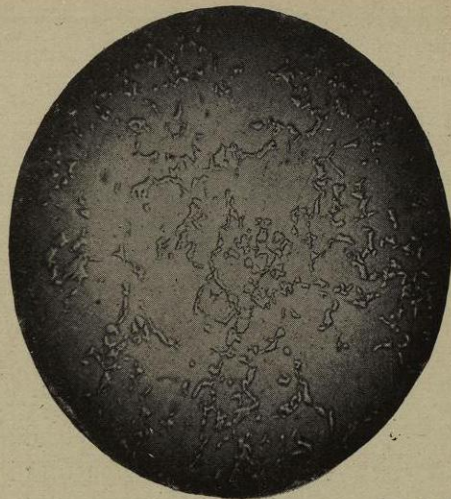


Fig. 160.—CARBON 0.45 per cent. Quenched at 690° C. Polished in bas-relief. $V \times 100$ diameters.

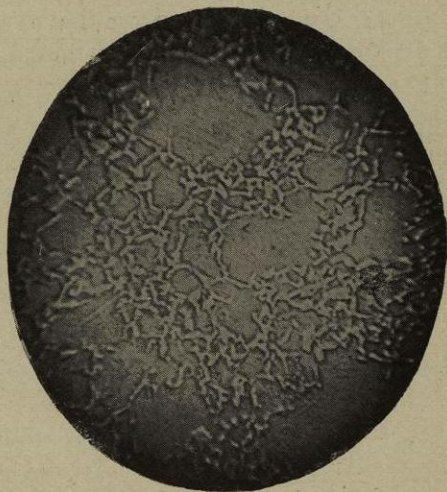


Fig. 161.—CARBON 0.45 per cent. Quenched from 670° C. Polished in bas-relief. $V \times 100$ diameters.

together. Liquorice-root, iodine, and nitric acid very nearly reproduce the structure which we have already found in the same steel heated and quenched at 730°.

A third sample was quenched at 670° between the maximum of $Ar_{3.2}$ and the beginning of Ar_1 . The general structure is still of the same type, but the isolated strips are united, and now form a thick and



Fig. 162.—CARBON 0.45 per cent. Quenched from 650° C. Etched with 20 per cent. nitric acid. $V \times 100$ diameters.

continuous cellular network easily developed by polishing in bas-relief (fig. 161, $V \times 100$).

A fourth sample was quenched at 650° during the course of the recalescence Ar_1 . The area of ferrite has again become what it was in the forged metal, and the appearance of the preparation polished in bas-relief is still the same. But attack for about two seconds by 20 per cent. nitric acid colours certain grains black and others only yellow (fig. 162, $V \times 100$). Some are

pearlite, that is to say, non-hardened steel; the others martensite, that is to say, hardened steel. The latter are attacked first at the centre, which is more sharply defined than the edges.

The recalescence having been passed, say at 640° , quenching does not produce any visible effect, and the structure of forged steel is reverted to.

(c) *Heating at a constant temperature (825°), followed by quenching from a constant temperature (720°) in different media.*

The baths chosen were—

1. A freezing mixture at -20° C.
2. Water at 15° C.
3. Water at 85° C., the effect of which is analogous to cold oil.
4. Melting lead.

We have seen from what has preceded that, after previous heating at 825° , to make sure of the diffusion of carbon, and quenching at 720° , the hardened metal was almost exclusively formed of martensite. It remains martensite after quenching in a freezing mixture.

But the mild quenchings at 15° C. occasion the formation of a network of ferrite almost as if the quenching had been done at a lower temperature in cold water. Fig. 163 (polish-attack: $V \times 1000$) shows, in white, the network of ferrite, the remainder being a marbled patina of different colorations. The needles of martensite have nearly disappeared, while the layers of pearlite have not had time to isolate. We have here to deal with transition forms between troosite and sorbite.

(d) *Influence of Tempering.*

If a plate quenched at 720° in cold water (after preliminary heating to 825°), be tempered from blue on

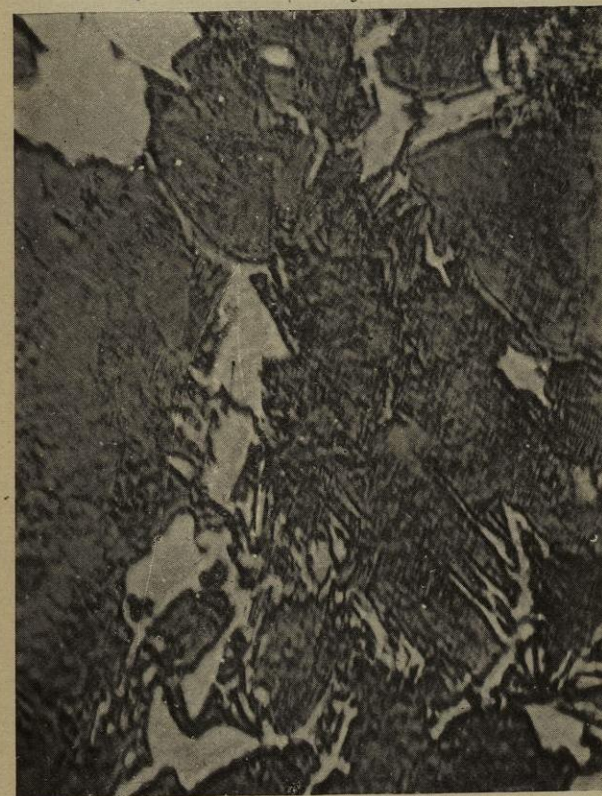


Fig. 163.—CARBON 0.45 per cent. Reheated to 825° C., and quenched on cooling at 720° C. in a freezing mixture. Polish-attack. $V \times 1000$ diameters.

the one side to brown on the other, polish-attack still allows one to catch a glimpse of the forms of martensite, but only vaguely and feebly. To obtain fig. 164

($V \times 1000$), it has been necessary to rub for a very long time, and to exaggerate the contrasts by strongly diaphragming the light. Attack with nitric acid shows

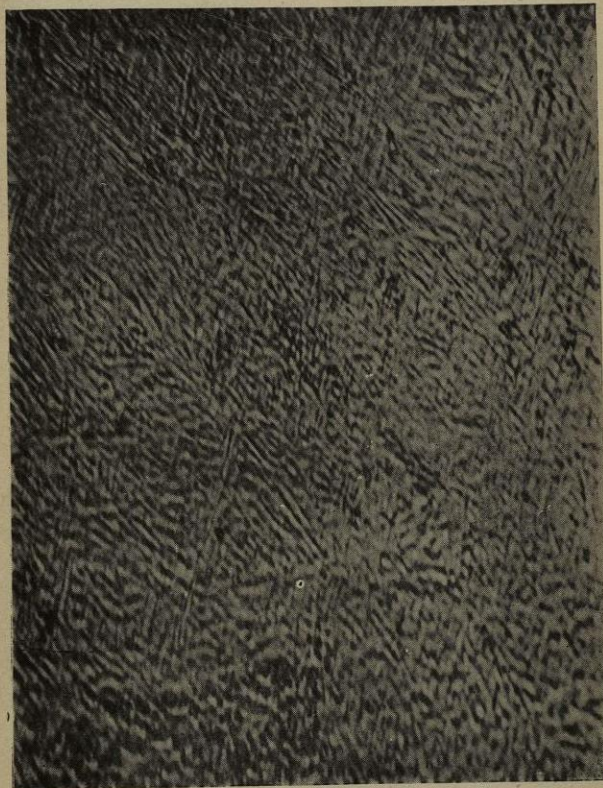


Fig. 164.—CARBON 0.45 per cent. Reheated to 825° C., and quenched from 720° C., and tempered to between blue and brown colour. Polish-attack. $V \times 1000$ diameters.

the triangles of martensite a little better, at least in some places. But the forms of martensite are here only the almost effaced image of the anterior structure, and no longer correspond to the actual state of the

associations of iron and carbon. Chemical analysis teaches us that cementite has been reconstituted; but it is in such a state of division that the microscope cannot identify it. A drop of iodine gives the whole preparation different colours mixed in the most complete disorder.

On carrying the tempering to 670°, we bring a little order into this chaos. The ferrite and cementite tend to separate, the former collecting into badly defined grains, around which the cementite is mixed up with sorbite (fig. 165: polish attack: $V \times 1000$). But the separation remains very imperfect.

Another disc, reheated and tempered at 600° after quenching at a white heat, is very instructive. There are met with, side by side, a herring-bone structure and well-preserved remains of the hardening structure. The grains of ferrite are encircled, without any sharp demarcation, by a network of sorbite, and a region in a state of transformation where the new structure is installed in the still visible framework of the old can be distinguished.

IV.—STEEL WITH 1.25 PER CENT. CARBON.

A. Forged Metal.—There is accidentally found, towards the axis of the specimen examined, a harder part which is reproduced in the majority of the samples.

This hard region is a good example of pearlite of the type shown in fig. 127, p. 175. In the rest of the disc the cementite has collected, probably by a forging terminated well below A_{r1} , into spheroids of variable size (fig. 166: polish in bas-relief: $V \times 1000$). In a harder steel forged under the same conditions, the

spheroids of cementite form parallel fibres, like the fibres of cinder in puddled iron, due to the forging.

B. Influence of Reheating.—Towards 750° the

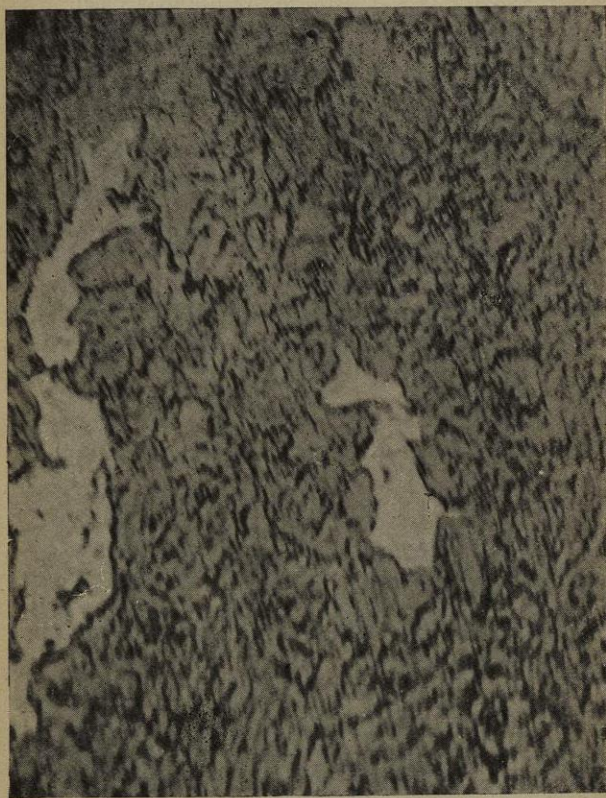


Fig. 165.—CARBON 0.45 per cent. Reheated to 825° C., and quenched from 720° C., and heated to 760° C. Polish-attack. $\times 1000$ diameters.

peculiar mixture we have just described, which we call *granulated* pearlite, is transformed to normal pearlite, passing more or less to sorbite, together with strips of independent cementite.

By reheating to 1015°, the hard nucleus is overheated and divided into beautiful polyhedrons by a continuous cellular network of cementite. At 1330° the mass is

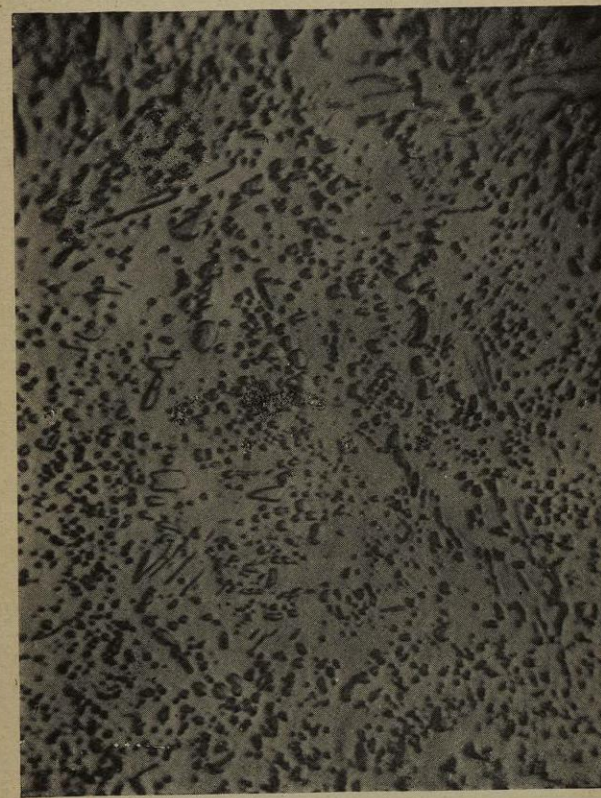


Fig. 166.—CARBON 1.25 per cent. Forged steel. Polished in bas-relief. $\times 1000$ diameters.

altogether burnt: the polyhedrons are of great size and frequently separated by a narrow border of ferrite, probably due to the introduction of oxidising gases. As for the remainder, the principal mass is always