more easily used, but also more easily extended, and that our errors may be corrected.

Laws Affecting Region IV of Fig. 68, the Structure of Austenite. — For given kind of steel it appears that for each temperature of region IV there is a normal size or diameter of grain (see end of § 216), and that the grain-size increases with the temperature. (Fig. 76a.) Let

D^n = the normal grain-diameter for given temperature T of region IV, for given steel.

The grain which actually exists at a given temperature in this region may or may not be of the size D^n. Let us call the existing size of the grain of the austenite then D^a to distinguish it from D^n, or

D^a = the existing grain-diameter of a given specimen when at a given temperature in region IV.

It appears that the normal size of grain increases with the temperature throughout region IV; this may be expressed by the following law:

[1], $D^n : D^{n'} = T : T'$.

Whether the normal grain-diameter is strictly proportional to the temperature as law [1] indicates, or whether it is proportional to some function of the temperature, remains to be seen. The line *JDG* in Fig. 76 is an attempt to represent this law. Prof. Sauveur and the author obtained for a certain specimen of steel* the expression $T^{max} = 680 + 281{,}250 \cdot a$ in which T^{max} equals the temperature reached, and a equals the actual area of the grain in square millimeters under a magnification of 250 diameters. This goes to show that the normal grain-size is strictly proportional to the temperature. It is in accordance with this that the lower part of this line has been drawn straight. But the curve by which Tschernoff represented the relation between the grain-size and the temperature differed from the line *JDG* as here drawn, in curving to the right through its whole length, from *J* upwards. As his results covered a higher range of temperature than ours a simple explanation is that, whereas the normal grain-size at relatively low temperatures or until the boundary *Aa* of

* The composition of the steel was: carbon, 1.10 per cent; silicon, 0.02 per cent; and manganese, 0.41 per cent. *Eng. and Min. Jour.*, LX, p. 537, Dec. 7, 1895.

region II is reached, is closely proportional to the temperature, yet at higher temperatures it may increase more rapidly than the temperature. With this in view, I have curved the upper part of this line.

We may, however, for simplicity, retain the form of law [1] already given, although it strictly implies that the line *JDG*

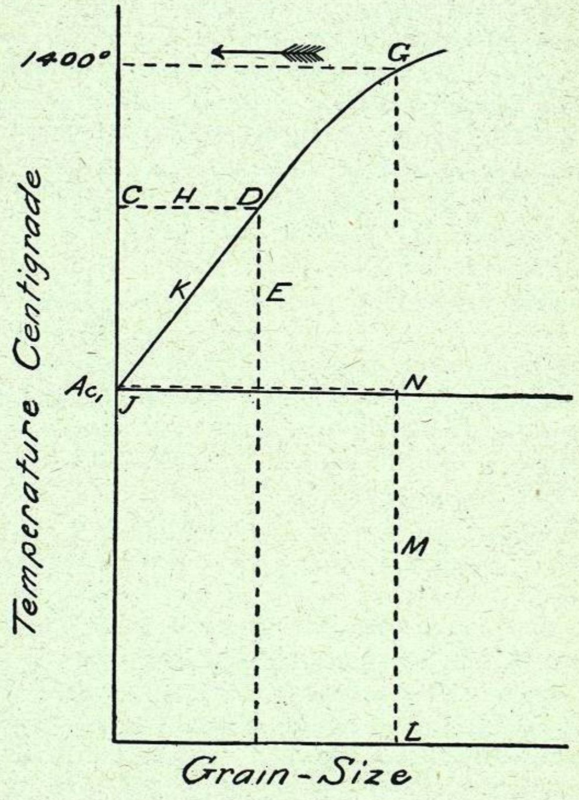

Fig. 76. Law [1]. **The Normal Grain-size of Eutectoid Steel in Region IV.** First Approximation.

is straight throughout. The slight inconsistency implied need not trouble us, if we remember that both the line *JDG* and the formula of law [1] are given as first approximations only; and that a formula prepared to fit the line as drawn might well deceive in implying for our knowledge a far greater degree of accuracy than it has.

Second Law of Grain-size. — At any given temperature in region IV, if the existing grain is smaller than that normal for the temperature, then the grains grow until they reach the normal size; or

[2] if $D^a < D^n$, D^a grows to D^n.

This growth is by no means instantaneous, but may occupy many hours. It is probable that the growth is at first very rapid, and becomes slower and slower as the existing size approaches the normal size.

Third Law of Grain-size. — If the existing grain is larger than that normal for the existing temperature in region IV, it does not shrink back towards the normal size, or

[3] if $D^a > D^n$, D^a does not shrink towards D^n.

An example may illustrate this. If in Fig. 76 we heat a piece of steel to say temperature *C*, and if we assume that the grain at the moment of reaching that temperature is of the size represented by *H*, then if the temperature remains at *C* the grain will progressively grow until it reaches the grain-size *D*, corresponding to *C*. If now, having reached this size, the steel is cooled to temperature *E*, the grain will remain of the size *D*, and therefore be far to the right of *K*, which represents the normal size for the temperature *E*.

Fourth Law of Grain-size. — If, now, we let

T^{max} = the highest temperature reached in the last sojourn in region IV,

and if we assume that the changes of temperature have been very slow, so that the grain has had opportunity to grow approximately to the size normal to T^{max}, then it follows from laws [1], [2] and [3] that the existing size of grain should be proportional to T^{max}; hence law [4],

[4] $D^a : D^{a\prime} = T^{max} : T^{max\prime}$.

This represents in a general way the law governing the size of the grains which we find in hardened, *i. e.,* suddenly cooled steel, which we may take to represent the size which the grain of austenite reached at the highest temperature touched in region IV.

As far as our present purpose is concerned it would have sufficed to define T^{max} as the highest temperature reached, without adding "in the last sojourn in region IV"; but we shall shortly see why this restrictive clause is added.

Laws Affecting Region VI and probably the left-hand part of region IX. Regarding this region from the point of view of its consisting of pearlite together with an excess of either ferrite or cementite over the pearlite ratio, we may let

D^p = the diameter of the grains of this region, or the pearlite diameter.

When steel cools from region IV into region VI it appears that the size of the grain which arises in region VI is at least roughly proportional to the grain which has existed in region IV, or law [5],

[5] $D^p : D^{p\prime} = D^a : D^{a\prime}$.

Indeed there is reason to think that the grain-size existing in region IV is the same as that to which it gives rise on passing into region VI: or in short (law [6])

[6] $D^p = D^a$.

Or in other words there is apparently no change of grain-size in steel on cooling past the critical range.

Thus it appears that there is no special grain-size to which each temperature in regions VI and IX corresponds; but that the steel in these regions simply inherits the grain-size which it had received in region IV.

Seventh Law of Grain-size. — From laws [4] and [5] it follows that if the steel has been exposed long enough to the highest temperature reached in region IV to grow to the size corresponding to that temperature, then the grain-size even after slow cooling will be proportional to that highest temperature, or law [7],

[7] $D^p : D^{p\prime} = T^{max} : T^{max\prime}$.

Indeed, this law should hold good in a rough way even if the foregoing conditions are not accurately complied with. Thus, if two like pieces of steel are heated to different temperatures in region IV, but at approximately like rates, then even if their sojourn at their highest temperature is not long enough to give each the full grain-size corresponding to that temperature, yet each will approach that limit of size towards which it tends. The grain-size of the more highly heated, growing towards its greater limit of size, will be correspondingly greater than the grain-size of the less highly heated, because the limit towards which the former tends is greater than that towards which the latter tends. Of these two pieces, then, it will be roughly true that the grain-size is proportional to the highest temperature reached in region IV, which is law [7].

Fig. 76a shows how the grain-size of the slowly cooled steel, or D^p, increases with the temperature to which the steel has been heated in region IV. Note the very coarse meshwork of the steel heated to 1339°, the finer meshwork of that heated only to 1212°, and the still finer meshwork of that heated only to 966°.

A most important inference from this law is that an inspection of the fracture, or of the microstructure in a polished section, indicates whether the steel has been unduly heated or not. To

Heated to

1339° C. 1212° C. 966° C.

and then cooled slowly.

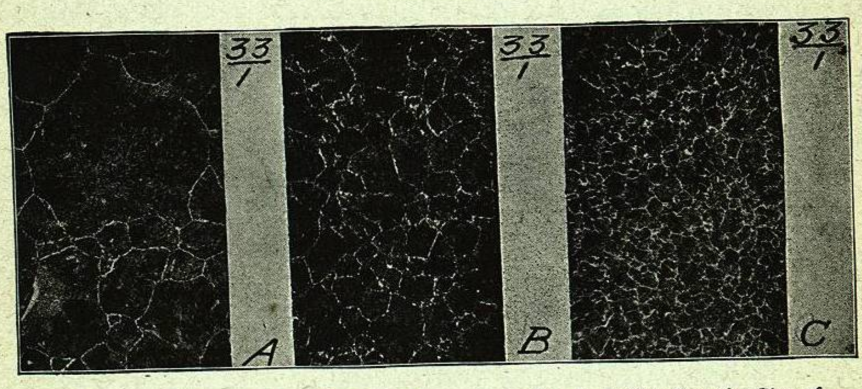

Fig. 76a. Influence of the Highest Temperature Reached (T^{max}) on the Size of the Grain of Slowly Cooled Steel. 33 Diameters.

Steel of 0.50 per cent of carbon.

Wm. Campbell, in the Author's Laboratory.

the practiced eye it indeed gives a surprisingly close measure of the temperature reached in region IV, of course not absolutely in degrees Centigrade, but relatively. It is probable that before many years we shall be able to formulate these laws with some precision, so that even the relatively unskilled can tell from the grain-size in the polished section to what temperature in region IV the steel has been heated, if the composition is known, and if the known conditions of the case tell us in a general way what the rate of heating has been. Such information can often be had

from the known conditions of the heating-furnace, the size of the piece treated, *etc.*

217. *Eighth Law,* Heat-refining. — This is probably of more direct practical importance to the practicing engineer than any of the other matters here considered. We may consider two sets of conditions, 1st, that applying to steel of about 0.90 per cent of carbon, *i. e.,* æolic steel, and 2nd, that applying to steel containing less carbon, *i. e.,* hypo-eutectoid steel.

Heat-refining of Eutectoid Steel.—If a piece of eutectoid steel which has been made coarse-grained by high heating in region IV, is cooled into region VI (whether to the room-temperature or only to some higher temperature in region VI), and is then reheated into region IV, during this passage across its narrow transformation region (represented in Fig. 68 as the point *S*), the old coarse grain, D^a, is broken up and a new finer grain results. This new grain will then become proportional to the temperature reached in this present sojourn in region IV. To show this let us turn again to Fig. 76. Let us suppose that a piece of steel has been heated to 1400° and has acquired the coarse grain of the size *G*, corresponding to that temperature, and let us further suppose that it is then cooled completely.

The grain-size of the cold steel may be represented by letter *L*. Suppose now that this steel is again reheated as shown by the dotted line *LMN*. Apparently no change in the grain-size is reached until the temperature rises past Ac_1, *i. e.,* until the steel enters region IV. But when this occurs, the old coarse grain appears to be completely wiped out, and a new grain, extremely fine, is established. The grain-size seems to follow line *LMNJ*. This may be called "Heat-refining."

This gives us law 8, *heat-refining, if the temperature of eutectoid steel is raised past the transformation-point* Ac_{1-2-3}, *the pre-existing grain is effaced and replaced by an extremely fine grain.*

The grain acquired in thus rising past Ac_{1-2-3} is so fine that the steel is often said to become amorphous; let this give us an idea of the extreme fineness, although it is more accurate to speak of such fine grain as porcelanic than as amorphous.

If, now, the temperature is further raised, then, quite as in the previous sojourn in region IV, the grain-size begins increasing with the rise of temperature along line *JDG;* and, after the steel is again cooled, its new grain-size, D^p, will represent the highest temperature reached in this last sojourn in region IV. It is thus the last sojourn in this region that determines the grain-size, both D^a and D^p; and it is for this reason that T^{max} was defined as the highest temperature reached in the last sojourn in region IV. We see that law [7] should hold good with this T^{max} thus defined.

Let it be distinctly understood that this refining is a thing which accompanies a rise past Ac_{1-2-3} but does not accompany cooling past the corresponding Ar_{3-2-1}. In other words overheated and coarsened steel is refined by heating from region VI or IX into region IV, but it is not refined by cooling from region IV into region VI or IX.

Hypo-eutectoid Steel. — The heat-refining changes which in case of eutectoid steel occur together at the triple critical point Ac_{1-2-3}, are in case of hypo-eutectoid and probably also of hyper-eutectoid steel, spread out over the whole of the transformation range, regions V and VIII.

The conditions of heat-refining here seem to be that pre-existing coarse structure is gradually weakened, without being changed in degree of coarseness, as the temperature rises from Ac_1 to Ac_3, *i. e.*, rises across region V; that the coarse structure finally disappears when the temperature enters region IV; and that during its weakening a new growth of grain-size within it occurs, starting at Ac_1 and continuing both across region V and through region IV. If Ac_3 is far above Ac_1, as happens when the carbon is very low, then by the time the old grain has been wiped out by the passage across Ac_3 the new grain which will have formed will be of considerable size; hence there is no such sharp refining effect with this steel as we find in case of eutectoid steel, because the old coarseness cannot be wiped out fully except by permitting a considerable growth of the new grain to occur.

If, on the other hand, Ac_3 is but little higher than Ac_1, *i. e.*, if region V is short (as in case of steel which is but slightly hypo-eutectoid), then the wiping out of the old coarse grain at Ac_3 takes place at so short a temperature-interval above that at which the new grain-growth has begun, that this new grain reaches only a small size; hence the heat-refining of such steel is nearly as complete as that of eutectoid steel.

In order to understand this condition of affairs, let us refresh our memory as to what it is that occurs as the temperature

crosses region V (Fig. 68). In cooling from region IV, when the temperature crosses *GHS* and enters region V, the excess of iron present over the eutectoid ratio of 99.1 per cent iron and 0.90 per cent carbon begins to separate out within the austenite, under many conditions forming a network, the coarseness of which depends upon the temperature which has been reached in region IV. In other words, the ferrite-excess which separates out as the temperature sinks below Ar_3 habitually segregates itself as a network, which may be continuous or rudimentary. But whether continuous or rudimentary its coarseness, in the sense of the size or width of the meshes which it encloses, is the measure of the grain-size. If these meshes are coarse, the grain-size is coarse; indeed each mesh with its bounding network may be considered as a grain. The size of these grains increases with T^{max}.

As the passage across region V continues, the separation of ferrite progresses, so that the ferrite network between the remaining austenite grains progressively thickens and becomes more strongly marked. This continues until the temperature reaches Ar_1, the lower boundary of region V, by which time the remaining meshes of austenite have gradually expelled into the encircling network all excess of iron over the pearlite ratio, *i. e.*, the hardenite ratio of 99.1 iron : 0.90 carbon; so that we now have a ferrite network of maximum thickness, encircling meshes of hardenite, *i. e.*, austenite of eutectoid composition. As the temperature sinks past Ar_1, *i. e.*, as the recalescence takes place, the austenite meshes change into pearlite, apparently without changing the encircling ferrite meshwork. For simplicity of description I pass by the progressive nature of these transformations, from austenite through the conditions of martensite, sorbite, and troostite, into pearlite. These are important, but not for our immediate purpose here.

As cooling continues through region VI this structure seems to persist unchanged, and indeed to remain unchanged during subsequent heating, until, as in heat refining, region V is again reached. On recrossing this region the changes which we have just traced again occur, of course in reverse order. That is to say, as the temperature rises past Ac_1 the pearlite of the meshes changes back into austenite of eutectoid ratio; as the temperature rises farther the network of ferrite is progressively reabsorbed by the austenite meshes, and thus grows thinner and thinner, but apparently without changing the size of the network. On thus reheating pieces cut from an ingot of hypo-eutectoid steel (carbon 0.56, silicon 0.14, manganese 0.18, phosphorus 0.02, sulphur 0.02), I could see, by comparing different pieces heated to different temperatures in region V, how the ferrite network gradually melted away, quite as narrow spines of ice would if floating in warm water. By the time the upper boundary of region V, Ac_3, had been reached, this network completely disappeared; its absorption by the austenite meshes had completed itself.

This progressive re-absorption of the ferrite network is what causes the gradual weakening of the old coarse structure, developed during the prior high heating in region IV. And the fact that this reabsorption is unaccompanied by any change in the situation of the individual members of the network, or in other words in the coarseness of the meshes which that network encloses, is the reason why the old coarse structure, as it fades and becomes feebler, still retains its old degree of coarseness. It has less and less effect in determining the path of rupture; but in so far as rupture follows this old coarseness, it yields the same old degree of coarseness of fracture.

But, while the old coarse structure has thus been fading away, a new and quasi-independent structure has been building up. For, following law [1], $D^n : D^{n'} = T : T'$, the austenite of the meshes is forming itself into new grains within the old network. These grains are grains of austenite not surrounded by any new network of ferrite, unless, having raised the temperature part way across region V we again lower it, in which case the ferrite which falls out of solution in the austenite as this cooling through region V progresses will form a new ferrite network, which will encircle these new austenite grains. In this case if we cool the steel completely, we find a two-fold network, (1) the remains of the older coarse structure, more or less effaced according to whether the temperature has risen much or little above Ac_1; and (2) within it the new, finer, ferrite network formed in the excursion into region V which has just taken place.

Thus it is that steel which is much hypo-eutectoid is not thoroughly refined by this process of heat-refining, because if the excursion into region V goes far enough to efface thoroughly the old coarse network, then the new ferrite network will, because of the extent of this excursion, because of the temperature interval

between Ac_1 and the limit of that excursion, be of very considerable size.

The researches of Mr. K. F. Göransson* when a student in my laboratory went to show that this is true of hyper-eutectoid steel also, in a general way.

217A. To find the Temperature of Heat-refining. — In case of steel containing between 0.40 and 0.90 per cent of carbon, the upper critical point, Ac_{2-3}, at which refining is completed, is that at which the magnetic properties are lost, apparently by the change of the magnetic *alpha* ferrite to the non-magnetic *gamma* iron of the austenite. So it comes that the refining temperature, in the sense of that necessary to complete the refining, is that at which the metal ceases to be magnetic. This temperature may readily be detected by noting whether the steel is or is not magnetic. A dipping needle can readily be made by hardening a high-carbon steel wire, magnetizing it, and mounting it in a small wooden roller. In seeking to learn the refining temperature, the steel which we are treating is heated slowly and from time to time removed and held beside such a needle, so as to learn whether it is still magnetic. In case of large steel objects a small piece of the same steel should be heated alongside of the large piece, and used for testing for magnetism.

217B. Stead's Brittleness.—The fact that the proportion between the free ferrite and the pearlite in very low-carbon steel is very different from that in high-carbon steel, naturally leads to somewhat different phenomena of heat-treatment, of which a very important one has been discovered by Stead.†

He found that, if the carbon-content is extremely low, say between 0.025 and 0.12 per cent, then the grain grows progressively coarser as the temperature rises from about 500° C., and instead of being refined, continues growing as the temperature passes Ac_1, say 700°, and beyond this continues growing, apparently until the temperature reaches Ac_2. From this point on no material change in size appears to take place until a temperature of about 900° C. (Ac_3), is reached, when the coarse grain is broken up and becomes refined.

* "The Effect of Reheating upon the Coarse Structure of Over-Heated Steel," *Trans. Am. Inst. Mining Engineers*, to appear.

† *Journal Iron and Steel Institute*, 1898, I, p. 145, and 1898, II, p. 137.