His results are expressed graphically at *A* in Fig. 77, and for ease of comparison the corresponding behavior of eutectoid steel is roughly sketched at *B* in the same figure. The dotted line in part *A* of this figure is to indicate that the grain of the austenite which is present at temperatures above Ac$_1$, begins increasing in size from the time when it begins to form, *i. e.*, as soon as the temperature rises above Ac$_1$.
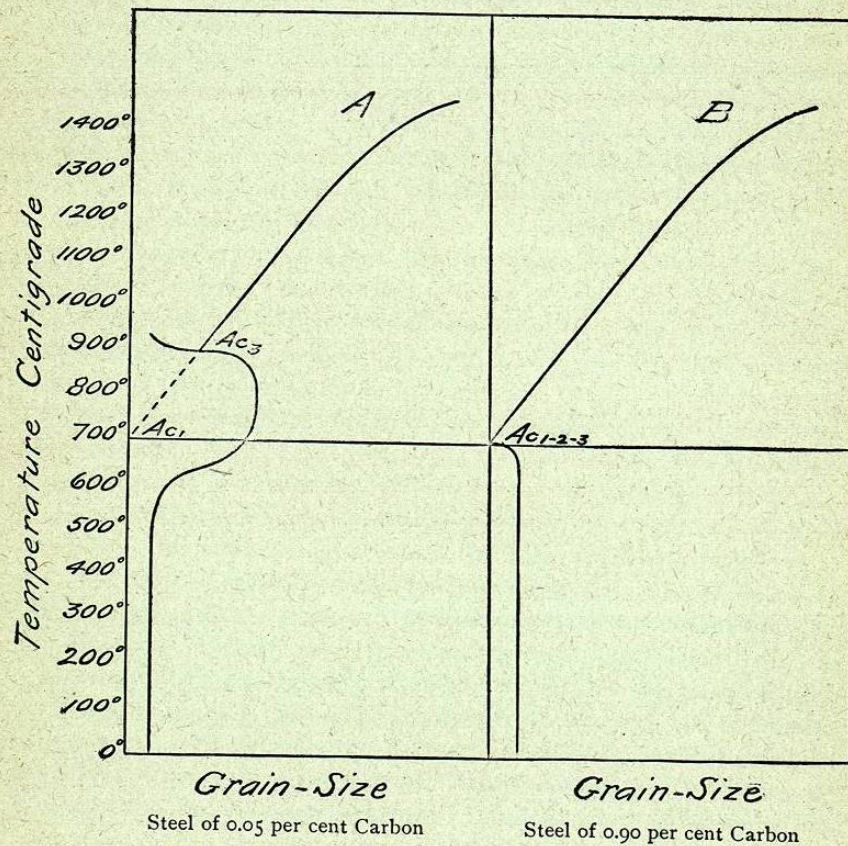

Fig. 77. Conjectured Relation between Temperature and Size of Grain of Steel. First Approximation.

In both classes of steel we have the phenomenon of the refining on passing Ac$_3$; in the low-carbon steel we have in addition the coarsening and embrittling on slow rise of temperature through the upper part of region VI. It is noteworthy and indeed natural,

that both forms of brittleness, that caused by overheating higher carbon steel, and that due to long exposure to a temperature of 500° to 700° in case of low-carbon steel, are cured and the metal is refined on heating past Ac$_3$; for in each case what here occurs is that the absorption of the ferrite by the austenite completes itself. In heating toward Ac$_3$ the quantity of free ferrite becomes progressively less; but as its absorption by the austenite progresses, its geographical position, if I may say so, does not appear to change; so that, as already pointed out, the size of the grain remains unchanged. It is on passing Ac$_3$ that the absorption of the ferrite completes itself, that this ferrite, the coarse granulation of which has caused the coarse grain and brittleness, itself disappears, and with it much or even in some cases all of the coarse grain and brittleness which had been caused.

So far, then, the two classes of steel behave in general alike, as is to be expected. But that they should behave differently on rising slowly through the upper part of region VI is not surprising, as the least reflection shows us. For if the carbon is from say 0.45 to 0.85 per cent, then the steel as a whole, in its slowly cooled or pearlite state, consists of a large important ground mass of pearlite, penetrated by a rather thin network of ferrite. If the carbon is very low, say from 0.025 to 0.12 per cent, as in the steels studied by Stead, then on the contrary the pearlite, instead of forming the greater part or at least an extremely important part of the whole, forms simply small scattered masses, in a great excess of ferrite. Under these conditions the coarsening and embrittling of low-carbon steel in the upper part of region VI are naturally referred to a coarsening of the ferrite, rather than to any change in the pearlite.

It remains to be seen how far like effects can be induced in higher carbon steel. Should it prove that steel of this kind is not subject to this ailment, or only subject to a mild form of it, we need not be surprised; for we naturally refer the grain-size of this steel to the size of the meshes of pearlite enclosed in the network of ferrite, rather than to the grain-size of the ferrite in that network.

218. BURNING.—Up to this point we have been considering only moderate overheating. But if the overheating is extreme, then the cohesion between the adjacent grains becomes so feeble that they are forced apart to a certain extent by gas evolved from

within. This gas probably consists, at least in part, of carbonic oxide, formed by the union of the infiltering atmospheric oxygen with the carbon of steel; though dissolved gases, hydrogen and nitrogen, may also contribute, being thrown out of solution by the rise of temperature. Such steel is said to be " burnt " as distinguished from that which is simply overheated; and we may provisionally adopt this distinction, that burning consists in a mechanical separation of the grains on extreme overheating.

There is another feature of burning, the great thickness of the network of ferrite which forms when this highly overheated and hence very coarse-grained steel cools through region V.

A   B

Fig. 78. Burnt Steel of 0.50 Carbon. 33 Diameters.
Made by W. Campbell, Ph.D., in the Author's Laboratory.

Burnt steel is recognized by its extreme brittleness both hot and cold, its coarse, shining fracture, and the oxide coating which we often find in that fracture. It is quite possible that the coarseness of this ferrite network may contribute to the effects of burning; but it is not easy to understand how it should come about that this alone and by itself should suffice to make the steel so incurably brittle. It should be possible to break up, by mechanical kneading, if not indeed by simple thermal treatment, the effects of this microscopic segregation of ferrite.

Fig. 78 shows the microstructure and also (in A) part of the fracture of burnt steel. The fracture was polished down, and the

parts here shown as level were then etched. They show the coarse grain of the austenite, especially when the small magnification (33 diameters) is taken into account. The depressed parts in A show the brightness of the fracture, and the smoothness of the surfaces along which rupture passes.

Burning, at least if extreme, cannot be cured by either heat-refining or mechanical refining. That heat-refining cannot cure it is natural enough. This process acts through inducing a metamorphic change in the continuous parts of the metal; its very nature shows us that it can have no power to close up mechanical gaps actually existing.

The following results obtained by one of my assistants illustrate roughly how the injury caused by overheating increases with the temperature reached, and how the curative power of heat-refining diminishes as the temperature passes from region IV into region II. Although these results have been on exhibition in my museum for some years, I owe this suggested generalization, that burning sets in with the passage from region IV into region II, to Professor Stansfield. Note that although exposure to a temperature of 1250° made the steel so brittle that it broke when bent through 14°, yet after refining it bent 144° before breaking. With higher heating the brittleness was only slightly increased, but the remedy which refining caused was relatively slight.

TABLE II. — *Brittleness Caused by Overheating, and its Cure by Heat-refining.*

APPROXIMATE TEMPERATURE (C.) TO WHICH THE STEEL WAS HEATED	DUCTILITY OF $\frac{5}{16}$ INCH SQUARE BARS OF STEEL OF 1.20 PER CENT CARBON ANGLE THROUGH WHICH THE PIECE BENT BEFORE RUPTURE	
	Bar not Refined	Bar Refined
1250°	14°	144°
1300°	7°	21°
1350°	4°	10°
1400°	3°	0°

It is in conformity with this idea that high-carbon steel is so much more liable to be burnt than low-carbon steel. The difference between these two classes in susceptibility to burning is too

great to be referred to the difference in the temperature at which freezing begins; it is to be referred rather to the steepness of the left-hand boundary *Aa* of region II. A natural inference, which should be tested, is that it is this boundary which determines the forging limit of temperature, as well as the temperature of burning. It is, indeed, to be expected that in any event the steel should be unforgeable in region II, because here it normally consists of a mechanical mixture of frozen austenite and of molten carburized iron. Such a mixture, part molten, part solid, could hardly be forgeable; the blows of the hammer should squeeze out the molten matter, and the whole should fall to pieces. This, indeed, is one of the familiar things which happens when we try to forge steel while it is at a burning heat.

As a palliative for burning, mechanical refining by rolling, *etc.*, is much more effective than heat refining, as we should naturally expect. For while heat refining should be powerless to close up even the most minute cracks, the compression and kneading which accompany mechanical refining should have a powerful effect in closing cracks even of considerable size, especially if their sides have not become coated with iron oxide.

218A. WHY DO NOT INGOTS AND OTHER CASTINGS BURN IN COOLING THROUGH THE BURNING RANGE? — It will at once be asked, how then is it ever possible to put into good condition any steel which has been cast in a molten state into ingots or other castings, since these evidently have in their initial cooling passed through every temperature between their melting-point and the cold, and hence necessarily through this range in which " burning," this incurable disease, occurs? Certain it is that ingots and other castings in thus cooling do not undergo burning, although steel bars heated to this temperature, whether cooled suddenly or slowly from it, are found when cold to have been incurably burnt.

Three explanations suggest themselves:

(1) That the burning is connected with the rise as such of temperature, and that simple cooling through this temperature cannot induce burning.

True it is that heating through a given range of temperature may have quite a different effect from cooling through it. But it often happens that a steel ingot, of which the outer shell has solidified while its interior is still molten, is set in a special form of heating-furnace called a soaking-pit; and parts at least of the

already frozen shell then are reheated very close to the melting-point by the heat of the still molten interior. Yet such ingots are not thereby burnt, although there has been a rise of temperature through the very range in which a bar of steel is burnt. Here then this explanation breaks down, and we reject it as incompetent.

(2) That burning is due to oxidation of the faces of the crystalline grains which compose the metal, by the inward diffusion of the atmospheric oxygen. These films of iron oxide, thin and discontinuous though they may be, may indeed be so distributed as to cause great weakness along certain planes; hence the injury which the high temperature causes. But when an ingot or casting is cooling from the molten state it gives off much hydrogen which had been dissolved as such or " occluded " in the molten metal. The outward working of this hydrogen may both mechanically restrain the oxygen from entering, and also counteract it. This explanation seems reasonable. It could be tested by learning whether a bar of steel heated close to its melting-point in vacuo or in an atmosphere of hydrogen is incurably burnt.

The explanation then is that in this burning range ingots and castings in their initial cooling are not burnt because protected by their evolution of hydrogen; but that bars of steel made from those ingots, having lost that hydrogen, are burnt in this range by penetration of the atmospheric oxygen along the crystal faces.

(3) That whether the burning is due to extreme coarseness of grain and to setting between the adjacent grains a network of ferrite so thick that to break it up and redistribute it is very difficult; or whether it is due to intergranular oxidation, the mechanical distortion and kneading which an ingot undergoes in rolling or hammering down into a bar is much greater than that which a bar can undergo in rolling or hammering down into a smaller bar; and that the former greater kneading suffices to break up and undo the work of burning much more thoroughly than the latter. The greater kneading which an ingot undergoes cures burning, while the slight kneading possible in reworking a steel bar does not.

This explanation does not suffice to show why a steel casting, which undergoes no mechanical work at all, is not burnt by cooling through the burning range. It is therefore incompetent to explain the phenomenon by itself. But, as castings in cooling

are generally protected from atmospheric oxidation by their moulds, this third explanation may be valid as contributory to the second. In other words, the fact that steel bars are burnt in a range in which ingots are not, may be due jointly to (2) the protection of the ingot by its own hydrogen from oxidation, and (3) to the more thorough breaking up of such thinner films of oxide as do form into relatively harmless minute separated particles through the greater kneading of the ingot.

We may therefore provisionally accept the second explanation, with the third as perhaps contributory.

219. MECHANICAL REFINING. — The coarse grain and its attendant brittleness induced by heating steel to the upper part of region IV can be cured by such mechanical distortion as occurs in rolling, hammering, and like operations. As austenite appears to belong to the isometric or cubic system, so its grains are normally equiaxed. The mechanical distortion in rolling and hammering elongates these grains in the direction of rolling and shortens them in the plane of the pressure; this appears to throw the metal crystallographically into unstable equilibrium, with the result that the old grains thus distorted break up, and that the metal rearranges itself into new and equiaxed grains.

But these new grains assume a size normal, not to the temperature at which the old ones had formed, but rather to the temperature now existing; during the rolling or hammering temperature is constantly falling; each pass through the rolls, and each blow of the hammer tends more or less fully to break up the pre-existing grain, and to substitute for it a new grain of a size more nearly normal to the now lower temperature. To speak more accurately, the new grain-size approaches that normal for the existing temperature; but the result is much the same. For if each of a succession of passes through the rolls breaks up the existing grain, and substitutes for it a new one, then each new grain will be smaller than the preceding, because the normal towards which it tends is smaller than the normal towards which its predecessor tended at the higher temperature then existing. (See end of § 219A.)

Fig. 79 attempts to express this condition of affairs graphically. Here ordinates represent temperature and abscissæ coarseness of grain. The line Ac_1A may be taken as representing roughly the normal size of grain, D^n, which steel of given com-

position tends to assume with varying temperature, or the line of normal coarseness of grain. If the grain is smaller than the normal for existing temperature it always tends to grow and to approach that normal (law [2]). If it is coarser than that normal it does not tend to shrink back towards the normal (law [3]), except when the temperature is *rising* past Ac_3 (law [8]).
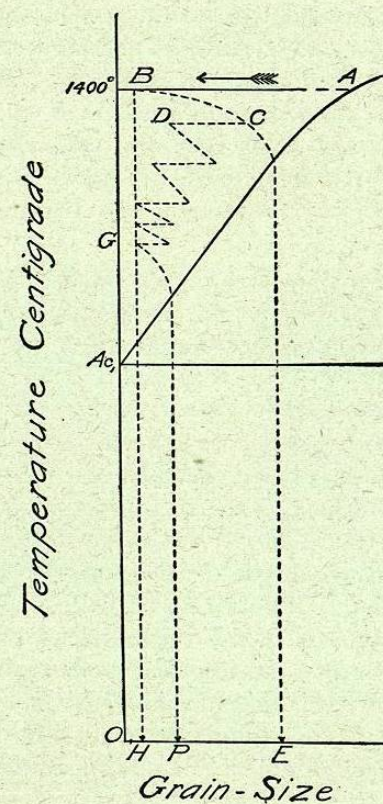

Fig. 79. The Influence of the Finishing Temperature on the Size of Grain.

Let us suppose that we cease rolling a piece of steel while its temperature is at B, the mechanical work of the rolls having broken the grain down. During subsequent cooling the grain will grow, somewhat as sketched in the line BCE. If, however, we resume rolling when the grain has reached C, we will again break down

the grain, and drive it back, say to D. And so, keeping on, between passes the grain grows and the temperature simultaneously falls, while at each pass the squeeze which we give the metal breaks up the grain, and the curve of grain and temperature follows the zigzag line *BCDG*.

If we cease rolling when the temperature has fallen to *G*, then the grain will grow as the metal cools, till the line of the actual size of grain intersects that of the normal size, the line Ac_1A; with further cooling no further growth ensues, and the final size of grain is *OP*. If we had quenched the metal while at *G*, the final size of grain would have been *OH*. If we had ceased rolling when the temperature was at *B*, the final size of grain in the cooled steel would have been *OE*. Needless to say, far from pretending that these curves are drawn to scale, I cannot even insist that their general teaching is true : but it certainly seems to harmonize with our phenomena.

219A. FINISHING TEMPERATURE.—If the foregoing views are correct, then it follows that the size of the grain will be the smaller the lower is the temperature at which the last distortion occurs, whether this distortion is caused by the last pass in the rolls or by the last effective blow of the hammer. Or roughly speaking, the grain-size will be the coarser the higher the finishing temperature ; this we may call the ninth law, or that of finishing temperature,

[9] $D : D' = FT : FT'$,

in which *FT* represents the effective finishing temperature.

Fig. 79a illustrates this principle. This shows the microstructure of two like bars of the same steel, of which each had first been heated to 1394° C., then cooled slowly to the temperature indicated in the figure, then rolled, and then cooled slowly, so that these temperatures are the " Finishing Temperatures." Note how much coarser the meshes are in *A*, finished at 963° C., than in *B*, finished at 837°.

This principle of governing the grain-size by means of the finishing temperature is of very great importance. In general we should be inclined by considerations of economy of power to roll or hammer steel as hot as we dare, because the hotter it is the softer it is, and the less power is consumed in rolling or hammering. But this would naturally lead to a high finishing temperature, and thus to coarseness of grain and brittleness. Hence a

high temperature is desirable as regards power-consumption, but undesirable as regards the quality of the steel.

To meet these two conditions it will often be well to lower the finishing temperature by some special device, while keeping the temperature high during much of the rolling so as to save power. For instance, in tire rolling the initial temperature is high ; but when the tire has been reduced nearly to the dimensions aimed at, a stream of water is turned upon it so as to hasten its cooling considerably, with the result that during the last part of the rolling the temperature falls rapidly, so as to give a low finishing temperature and a fine grain.

Microstructure of Steel of 0.50 per cent of Carbon
Heated to 1394° C., then cooled slowly to
963° (A)   837° (B)
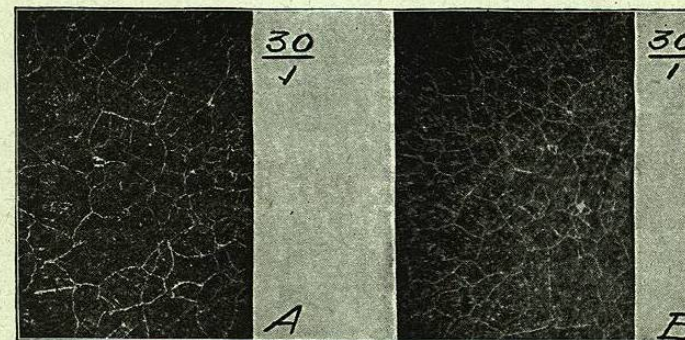then rolled, and then cooled slowly.

Fig 79a. Influence of Finishing Temperature on the Size of the Grain of Steel of 0.50 per cent Carbon.
Micrographs by Wm. Campbell in the Author's Laboratory.   30 Diameters.

This steel, which is the same as that shown in Fig. 76a, was heated to 1394°, then allowed to cool to the temperatures indicated in the figure, then rolled, and then cooled slowly.

In rail rolling a like purpose is kept in view. Because the head of the rail is so much thicker than any other part, it tends to cool much more slowly than the rest during the operation of rolling the initial square bloom into the final shape of the finished rail ; or in short the head tends to have a much higher finishing temperature than the rest of the rail. To meet this trouble, in