CHAPTER XVIII.

HEAT TREATMENT OF STEEL.

WHAT is called the "heat treatment" of steel—*i.e.*, the whole of the thermal conditions to which the material is subjected from the time it is cast until it is ready to leave the manufacturer's hands—is now recognised as being of the utmost importance in steel manufacture, and is receiving more and more attention from practical men. The great influence which heating to varying temperatures has upon the crystalline structure and physical properties of the metal can be demonstrated by a very simple experiment which anyone can perform for himself. Take a piece of steel, 10 to 12 inches long, and about $\frac{3}{4}$ to 1 inch in diameter, nick it at distances of about 1 inch apart, and then heat one end to a full welding heat in a smith's forge and allow to cool naturally or quench in water. Now break off pieces of the bar at the points where it has been nicked and compare the fractures of the different pieces. The first piece which has been heated to a full welding heat will have a coarse crystalline structure, and will readily break off at the first blow of the hammer, the next inch will be finer in fracture, and each succeeding piece will be finer than the last until that part of the steel is reached which has only been slightly heated, when the differences in fracture will be hardly perceptible, the grain being uniformly fine.

The crystalline structure of steel in relation to heat is affected principally by five factors—viz., temperature, time of heating, mass, rapidity of cooling, and whether the steel is allowed to cool slowly undisturbed, or whether it is forged or rolled during the cooling period. The question of mass is most important, and so far as systematic experimental work is concerned little has been done to investigate its influence, although no doubt many manufacturers have studied this question so far as it relates to their own particular branch. It is of course intimately connected with time, as the larger the mass the longer the time necessary to heat it to its centre, and thus the outside of a large casting or forging may be heated for a considerably longer period than the inside, and consequently different parts of the same forging will have been subjected to different heat treatment. The marked influence of work on the structure, and consequently on the physical properties of steel, is shown in the case of welding. On heating a piece of steel to full welding heat and allowing it to cool undisturbed, it will have a large crystalline structure and be comparatively brittle, whereas the same steel, if well hammered to weld it to another piece, will be fine in structure, tough and ductile.

In everyday practice steel has to be heated to different temperatures to give it the required degree of plasticity for rolling or forging into shape, and frequently afterwards reheated or annealed to redistribute stresses produced by working and to induce certain changes in the crystalline structure of the material. In other cases it has to be heated previous to hardening and tempering, and different treatment is required to produce the best results desired in each case. It is, therefore, desirable to get clear ideas as to the object of each of the above operations.

Annealing.—The object of annealing is to redistribute and remove as far as possible all internal stresses in the material induced by rolling, forging, or any other kind of work, and to bring the metal into the best physical state to resist fracture under sudden stress. Annealed steels should possess the maximum degree of ductility and softness to the file, combined with the highest possible elastic limit. Annealing may therefore be defined as the heat treatment, preferably in a reducing or neutral atmosphere, which produces the maximum amount of ductility, combined with the highest elastic limit. The particular temperature to which a steel must be heated will vary with the Carbon content.

Hardening.—It has already been pointed out in Chap. xv. that when steel containing over ·2 or ·25 of Carbon is suddenly cooled by quenching in water or other media, the steel becomes hard, the hardness varying with the percentage of Carbon present, and within certain limits with the temperature from which the steel is cooled, and the rapidity of cooling. If heated and quenched from too high a temperature the steel will be liable to be brittle, and if from too low a temperature it will not be sufficiently hardened. In hardening, one should therefore aim at heating the steel to the particular temperature, and suddenly cooling it by quenching in water or other medium which will confer the maximum degree of hardness which the particular grade of steel is capable of acquiring.

Tempering.—The hardness conferred upon steel by rapid quenching is not suitable for many industrial purposes, and has to be modified or "tempered" to suit the particular requirements of the case. This may be done by reheating the hardened steel to different temperatures. The operation of tempering may therefore be defined as the modifying of the degree of hardness conferred upon steel by quenching, by heating to certain definite temperatures, followed by slow or rapid cooling. Tempering reduces the brittleness and the hardness, and considerably increases the toughness and ductility of the material, and by varying the conditions of heat treatment almost any required degree of hardness may be produced.

Many years ago Brinell investigated the relation of the structure of steel to its physical properties as influenced by heat treatment, and came to the conclusion that the finer the structure the stronger the steel, and that the object of heat treatment should therefore be to obtain as fine a structure as possible. Brinell made an exhaustive series of experiments on a steel containing ·5 per cent of Carbon, and found there was a certain definite range of temperature to which it was desirable to heat such steel in order to confer upon it the finest structure, whether the steel was allowed to cool slowly or was quenched from this temperature. This range of temperature he further found was identical with that during which the Carbon changed to or from hardening Carbon. The particular temperature at which the Carbon passes from the *cement* to the *hardening state* is accompanied by a change from a more or less coarse to a very fine or amorphous structure, and this he denoted by the letter W, and the best results in hardening were obtained by heating to this temperature previous to quenching; if this temperature be exceeded the steel will become more crystalline and more or less brittle, and if this temperature is not reached the steel will not fully harden. When the steel is heated to any temperature above W the Carbon is always found in the hardening form.

The temperature at which the reverse change of state of Carbon—viz., from the *hardening* to the *cement form*—has the greatest tendency to take place during cooling, Brinell denoted by the letter V, and this he considered the most suitable for the annealing or softening of steel. When the steel is heated to any temperature between V and W * the Carbon passes from the cement form to hardening Carbon; heating above this temperature does not affect the Carbon condition. On heating to the temperature W or higher the

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* If Brinell's point W be taken as the Ac_1 change, it is now recognised that it is necessary to heat above W to convert cement Carbon to hardening Carbon.

steel assumes the same structure, *no matter what its structure before the heating may have been.* This is due to the fact that the complete transition of the cement Carbon into hardening Carbon at W is always accompanied by a change to finest structure, which on further heating again becomes coarse.

On heating to a temperature *below W the structure developed will depend on the structure and Carbon condition before heating.*

The above points, W and V, correspond to the critical points observed during the heating and cooling of steel, respectively known as Ac_1 and Ar_1. Thus, W corresponds to the passage of cement Carbon into hardening Carbon during the heating of steel, which transformation is accompanied by a retardation in the rate of heating indicating an absorption of heat. This temperature, W or Ac_1, is generally about 30° C. higher than V or Ar_1, and often covers a range of 25° to 30° C. The temperature indicated by V corresponds to the recalescent point Ar_1 observed during the slow cooling of steel, during which the Carbon passes from the hardening to the cement form—a change accompanied by a retardation in the rate of cooling, indicating an evolution of heat which is sometimes so considerable as to produce a visible rise of temperature in the steel: this is the well-known recalescence point. It will vary somewhat with the grade of steel, being lowest in higher Carbon steels; in medium and hard steels it is generally situated between about 650° and 700° C., and covers a range of about 20° to 30°, but in softer steels it occurs at a higher temperature, and in practically carbonless steel is hardly perceptible at all.

From Brinell's experiments, then, it appears that, to obtain the best results in hardening, steel should be heated about 30° C. above the recalescent point Ar_1 before quenching, and, for annealing, to above the recalescent point but below W.

In 1899* Sauveur, in a paper before the Iron and Steel Institute, gave a most complete summary of the structural changes induced by heat treatment in Carbon steels as revealed by the microscope, which is so concise and clear that it is given *in extenso* as a series of propositions, especially as it practically includes and confirms the most essential points in Brinell's results.

Changes of Structure Brought about by Heat Treatment.

"1. When a piece of steel, hardened or unhardened, is heated to a temperature W, all previous crystallisation, however coarse or however distorted by cold work, is obliterated and replaced by the finest structure which the metal is capable of assuming,† the structure of burnt steel, which cannot be effaced by such treatment, being the only exception.

"2. When a piece of steel, hardened or unhardened, after being heated to the temperature W, is allowed to cool slowly, it retains the fine amorphous-like structure which it had acquired at that temperature. It possesses then the finest structure which unhardened steel is capable of assuming.

"3. When a piece of steel, hardened or unhardened, after being heated to the temperature W, is suddenly cooled from that temperature—by quenching it in cold water, for instance—it is fully hardened,* and retains the fine amorphous-like structure acquired at that temperature. The metal possesses then the finest structure which hardened steel is capable of assuming.

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* *Iron and Steel Inst. Journ.*, 1899, vol. ii.

† It has been stated by Coffin that in the case of soft steel (containing ·2 per cent. of Carbon) a single heating to W breaks up only partially a pre-existing coarse crystallisation, a second reheating to that temperature being necessary to obliterate it altogether. This point should be further investigated. Some steel castings also are said to require more than one heating to W to assume the finest possible structure.

"4. When a piece of steel, hardened or unhardened, is heated to a temperature above W and allowed to cool slowly and undisturbedly, the metal, whose crystallisation had been obliterated by its passage through W, crystallises again, the crystals or grains increasing in size until the temperature V is reached, below which there is no further growth.

"*Corollary to* 3 *and* 4.—When a piece of steel, after being heated to a temperature above W, is allowed to cool to W, and then quenched, it will be fully hardened, but its structure will be coarser than if it had been quenched from W without having been previously heated above that temperature.

"5. The higher the temperature above W from which the steel is allowed to cool undisturbedly, the larger the grains.

"6. The slower the cooling from a temperature above W, the larger the grains.

"*Corollary to* 5 *and* 6.—Pieces of steel finished at a temperature above W will have a coarser grain in those parts which have been finished hottest, and where subsequent cooling has been more gradual—*i.e.*, the central portions, or portions further away from the cooling surfaces.

"7. When a piece of steel, hardened or unhardened, is heated to a temperature above W and suddenly cooled, it is fully hardened, but its structure will be coarser than when quenched after having been heated to W.

"8. When a piece of unhardened steel is heated to a temperature below W and quenched or slowly cooled from that temperature, no change takes place in its structure.

"9. When a piece of hardened steel is heated to a temperature below W, some of its hardening Carbon is changed spontaneously into cement Carbon, and the metal is thereby softened. The tendency of the hardening Carbon to pass into the cement condition increases with the temperature, and is the greatest at the temperature W. This transformation, however, is not accompanied by any change in the dimensions of the grains.

"These propositions are for the most part illustrated in fig. 259 in which I have adopted Brinell's mode of representation."

As referred to below, Stead has shown that large or coarse crystallisation is developed in steel containing ·11 Carbon or less by prolonged heating below W, and proposition 8 is, therefore, true only of steels containing over ·2 of Carbon.

Brinell, as the result of experiments with ·75 Carbon steel, came to the conclusion that not only will the hardening Carbon in a piece of steel, previously hardened by quenching from W, be completely changed to cement Carbon on heating to V, but that the structure will also be as fine as if it had been heated to W. Sauveur agrees as regards the Carbon change at V, but his microscopic examinations show no change in size of

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* It is evidently meant here, and in all similar references, that after heating to the above temperature, the steel under consideration will acquire all, or practically all, the hardening power which that particular steel is capable of assuming, no further increase of hardness resulting from quenching at a higher temperature. Its absolute degree of hardness will, of course, depend upon its Carbon-content, rate of cooling, and the presence of other impurities; in the case of the softest steels, the increase of hardness may be very nearly, if not altogether, inappreciable. Very low Carbon steels, moreover, do not seem to acquire, in its entirety, during W, whatever hardening power they possess, it being necessary for that purpose to heat the metal to a higher temperature—*i.e.*, pass the upper retardation.

the grain. Stead has confirmed Sauveur's results in this respect, and it is probable, as suggested by the latter, that the finer appearance of the fracture observed by Brinell is due to a distortion of the crystals, and that there is no actual change in structure.

Stead,* as the result of a most exhaustive series of experiments on low Carbon steels, found that they became coarsely crystalline on prolonged heating at a temperature between 600° and 750° C., but such crystallisation was not always attended with brittleness. On close annealing tin plate bars for forty-eight hours at 700° C. the crystalline structure was developed, and on repeating the annealing it became more and more marked, many of them fractured readily on bending, and all broke on bending to an angle of 60° and straightening. On reheating these bars to 900° C. and allowing them to cool naturally, they became exceedingly tough, and could be bent backwards and forwards without breaking, and a coarse crystalline layer, developed during the first annealing on the outside of the bar, no longer existed.

Ridsdale has confirmed Stead's results that this brittleness produced in mild steel by prolonged heating at a low temperature is removed on reheating to about 900° C.

Stead considers there are two sorts of weakness in low Carbon steel which tend to make it brittle, one weakness between the grains or crystals, which he calls intergranular weakness, and one due to true cleavage planes through the body of the crystals. It is admitted by all metallurgists that, other things being equal, the finer the grain the tougher the material, and this is largely due to the fact that the grains, as a rule, arrange themselves heretogeneously with their cleavage planes at varying angles to each other, but some exceptional cases of brittleness in fine-grained steel may be due to the crystals being arranged so that their cleavage planes lie in one direction, when we should expect that any sudden shock would tend to produce fracture along this line. Mild steel sheets which have been annealed frequently fracture in certain fixed directions, during stamping, at an angle approximating to 45° to the direction of rolling. The author has frequently had to deal with large quantities of sheets which were perfectly ductile, and could be bent close in certain directions, but invariably failed on stamping by fracturing in straight lines. Stead was the first to point out the connection which invariably exists between the lines of fracture and rolling, and that the fracture was a true cleavage fracture through the crystals. Heating up to 900° C. completely removes this form of brittleness.

Brinell states that in forging fairly high Carbon steel the greatest care should be taken that the temperature does not considerably exceed W, and that the forging should be continued until a temperature of a low red heat is reached to obtain the best results.

Campion† has published the results of a number of experiments on the heat treatment of steels containing from ·1 to ·5 per cent. of Carbon, more especially with reference to annealing, his object being to determine the best conditions to obtain the "highest ductility and mineralogical softness combined with the highest possible elastic limit, accompanied in all cases by fine grained microstructure." Steels possessing the above physical characteristics, he considers, are in best condition for resisting sudden shock, which is the best practical test we have as to the efficiency of the annealing. He particularly emphasises the importance of the length of time of heating in addition to the temperature, and the following may be taken as a short summary of about 180 experiments.

Soft steel, such as is used for constructional purposes and containing

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* *Iron and Steel Inst. Journ.*, 1898, vol. ii.

† *West of Scot. Iron and Steel Inst. Journ.*, vol. vii., p. 2, and vol. viii., p. 3.

s o rostructure brought abou

[*To face p.* 432.

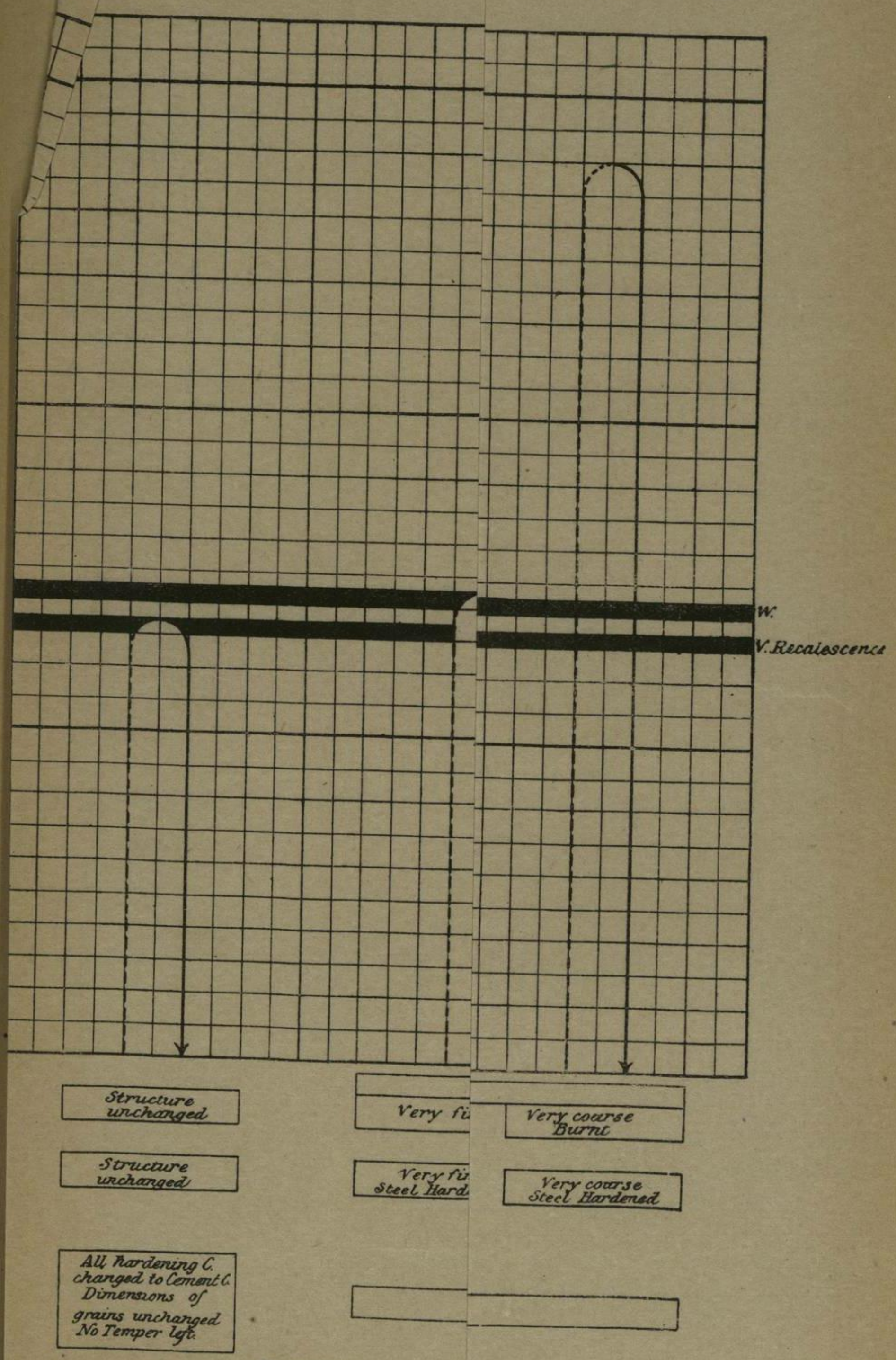

Fig. 259.

PLATE XVII.—Changes of Microstructure brought about in Steel by Heat Treatment.

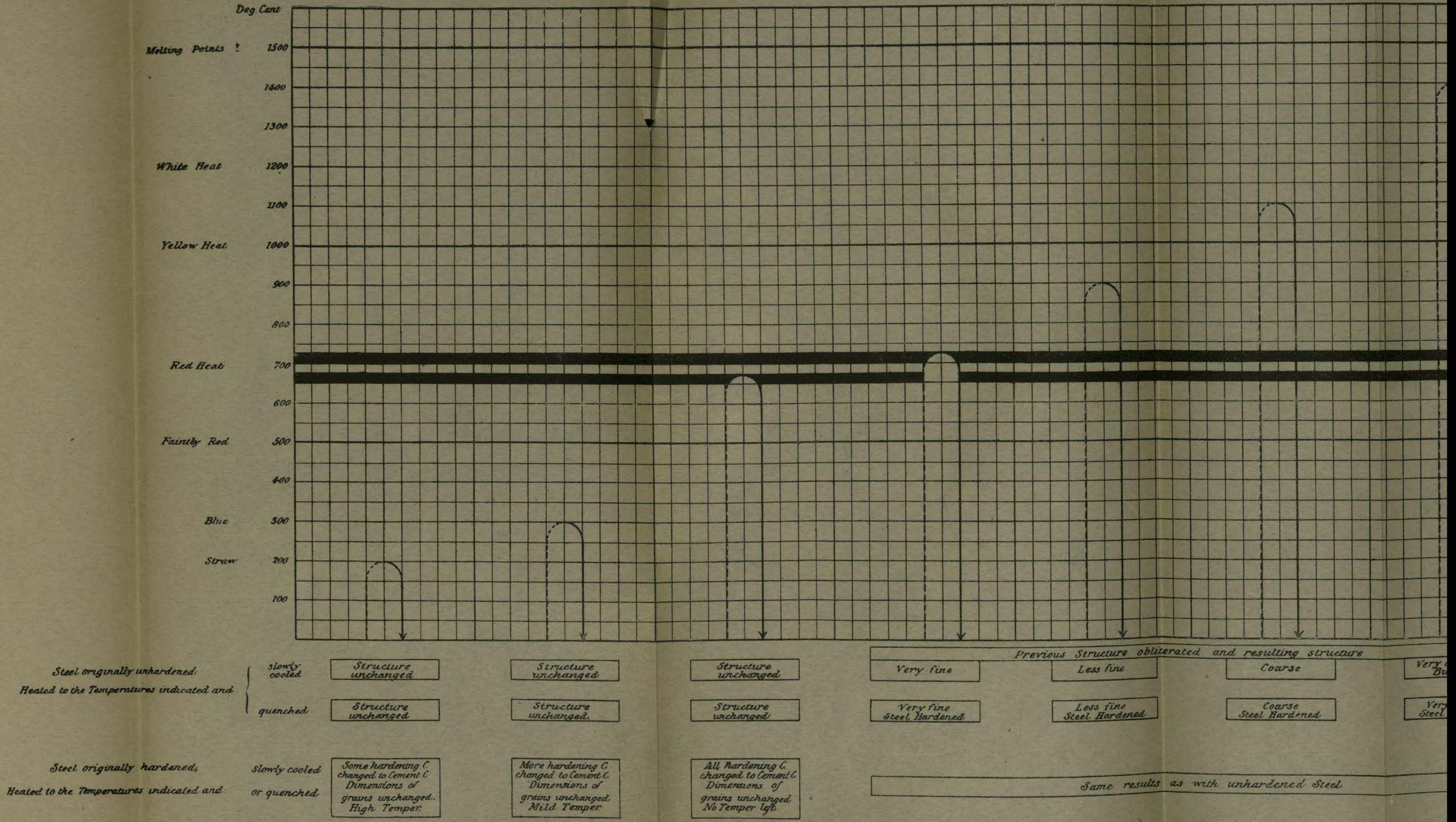

Fig. 259.

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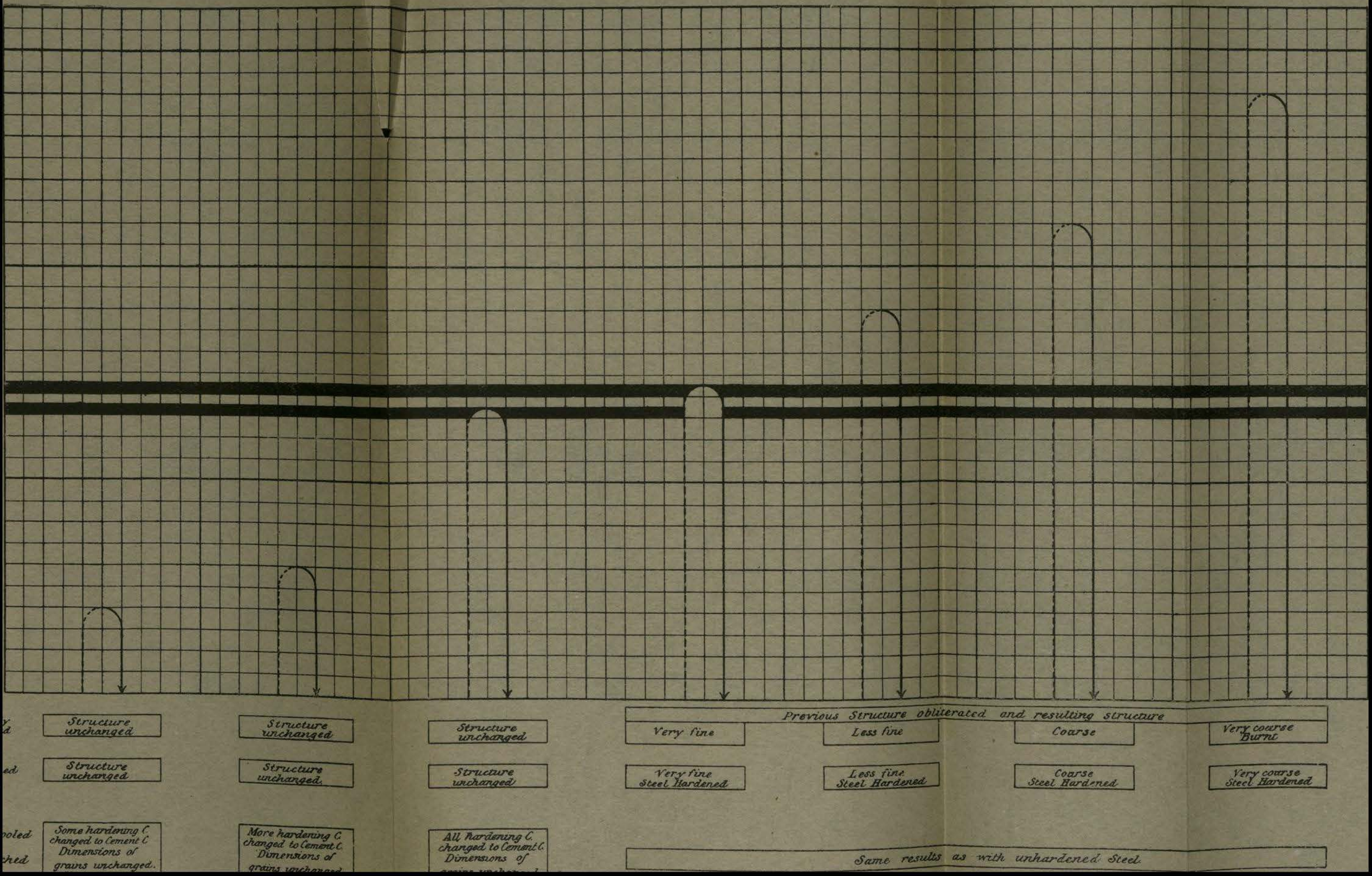

about ·15 per cent. of Carbon, appears to be improved in ductility, and to have a finer grain, after being heated to temperatures between 730° and about 850° C. for periods of time varying according to the temperature to which it is raised. If the higher temperature is selected, the pieces must be held there for only a very short time; but he is strongly of opinion that it is unsafe to heat to a higher temperature than about 800° to 820° C. It seems to be an essential condition to obtain a fine-grained microstructure that the piece should be heated as rapidly as possible. He obtained the most satisfactory results by heating rapidly to about 750° C. for a moderate time, and subsequently slowly cooling through the critical range Ar_1, or the V of Brinell, the point at which the transformation from hardening to cement Carbon takes place. The cooling should be fairly rapid until the beginning of Ar_1 is reached (which is between about 710° to 640° C. for soft steel), but should then be as slow as possible, that the transformation of Carbon may be complete.

The metal appears then to possess its maximum amount of ductility, accompanied by fine microstructure, and to be in the most suitable condition to withstand sudden shock. In the case of very soft steel containing, say, ·1 per cent. of Carbon, he found that a single heating to Ac_1, or the W of Brinell, does not always suffice to completely convert the hardening to cement Carbon, and that a second heating to a temperature exceeding V is necessary to give the finest possible grain structure, which confirms a similar statement made by Coffin many years ago.

Heating to a temperature not exceeding Ar_1, or V, he finds, does not produce a fine-grained microstructure, but a prolonged heating at the temperature Ar_1, or V, will effect the complete transformation of the hardening to cement Carbon, with practically no alteration in the size of the grains. This is true of all steels, excepting very soft steels and practically Carbonless iron, which may (as Stead and Ridsdale have shown), on prolonged heating between 600° and 700° C., develop a very coarsely crystalline structure, and produce great brittleness of the metal. This confirms Sauveur's results.

In the case of steel containing about ·35 per cent. Carbon, Campion found the limits of temperature to which the metal should be heated are less wide, apparently the maximum is 800° C., and that for only a very short time; heating for a moderate time at about 700° to 720° C. seems to give the best results.

The steel with ·44 per cent. Carbon gave good results when heated between 620° and 720° C. He is of the opinion that the most suitable temperature for this grade of steel is about 660° C., but much more work is necessary before anything can be definitely stated on this point.

The results of experiments on heating for several hours between 600° and 700° C. seem to confirm the results obtained by other experimenters, that a prolonged heating *below* the critical point Ar_1 does not produce the detrimental effects which it does in the case of soft steels.

The question of the heat treatment of mild steel has also formed the subject of a very complete investigation by Professor Heyn,* the ductility of the material being tested by bending tests, and his experiments, although confirming those of other investigators in many respects, in some give different results. He finds that the fracture of overheated mild steel generally shows a coarse grain, although this is not necessarily always the case, and depends upon the rate of cooling. The structure of overheated steel usually shows large ferrite crystals, but he does not consider such structure a proof that overheating has taken place, as the same structure

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* *Iron and Steel Inst. Journ.*, 1902, vol. ii.

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* *Iron and Steel Inst. Journ.*, 1902, vol. ii.

may be produced by prolonged heating between 700° and 890° C., although such structure is not necessarily accompanied by brittleness.

When mild steel is annealed at temperatures above 1,000° C., the brittleness of the material is increased if the annealing period is sufficiently long, and the higher the temperature the sooner this brittleness increases and manifests itself. Within certain limits it is possible to produce almost any desired degree of brittleness by varying the temperature and time of annealing. Between 1,100° and 900° C. there exists a definite "temperature limit," *above which*, if annealing is carried on for a longer time at an increasing temperature, the degree of brittleness increases, but *below this limit* brittleness *does not increase.* Overheating not only occurs at an extreme white heat, but becomes apparent at much lower temperatures, provided such temperature exceeds the "temperature limit," and its effects are more marked the longer the period of heating. Professor Heyn differs from Stead and other investigators as to the effect of prolonged annealing at low temperatures, as, according to his results, not only is there no increase in brittleness, but it may actually be decreased by heating for long periods between 700° and 890° C., whereas Stead found low Carbon steel was made extremely brittle by heating between 600° and 750° C.

He confirms Stead's results that the brittleness induced by overheating mild steel can be eliminated by annealing at 900° C., and that the short period of half an hour is sufficient to produce this result, and longer annealing should be avoided. Below 800° C. annealing for five hours did not remove this brittleness, but it was removed by heating for several days at a temperature between 700° and 850° C.

It seems probable that the apparent differences between the results obtained by Stead and Heyn on prolonged annealing, at temperatures under 850° C., are due to some slight variations in the temperatures, as Stead's experiments were made at temperatures of from 600° to 750° C., while Heyn's were at 700° to 890° C. Assuming Stead's samples were heated nearer the lower (600° C.), and Heyn's at or near the higher limit (850° C.), this would be quite sufficient to explain the different results obtained, as we know that mild steel is extremely sensitive to comparatively small variations in heat treatment. Heyn confirms the experience of practical men that mild steel, which has been annealed at a temperature so high that if allowed to cool undisturbed it would be brittle, will exhibit no brittleness when cold, if, while cooling, it has been rolled or forged at a bright red heat.

The influence of work on the size of grain of soft steels has been investigated by Ridsdale,* who states that the size of grain is inversely proportional to the sectional area in normal steels, provided the sections are of such size that they are finished below the critical temperature of Brinell, but not below a dull red heat. This only applies to steels of the same composition, and subjected to similar conditions as to heat treatment. In the same paper Ridsdale gives the results of a large number of experiments on the normal and abnormal heat treatment of various steels, with and without work.

Sauveur † states that steel does not crystallise while it is being worked, and that work above the temperature W has no direct influence upon the structure, but that indirectly, by retarding crystallisation until a lower temperature is reached, it may have a most marked effect. The effect of work at any temperature below a dull red heat is to distort the grains or crystals of the steel, and the lower the temperature the greater the distortion, but such structural deformation, with its accompanying alterations of the

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* *Iron and Steel Inst. Journ.*, 1899, vol. ii., p. 113.

† *Ibid.*, 1899, vol. ii.

physical properties of the metal, may be removed by subsequently heating to W.

An important paper on the heat treatment of steel was read before the Iron and Steel Institute at the May meeting, 1903, by Campion,* one of the Carnegie scholars, for which he was awarded the Carnegie gold medal. The results are of great practical utility, as the experiments were made on bars varying from 1½ to 6 inches diameter, and of the same Carbon content, thus showing the influence of mass. It will be seen that the annealing temperature giving the best results varied from 600° to 850° C., according to the composition of the steel and the size of the bars. The following is a summary of the results :—

Small sections of rolled steel containing ·2 per cent. Carbon can be heated between very wide limits of temperature without seriously impairing their power of resisting sudden shock, as shown by results of bending tests. The results of the experiments indicate, however, that 850° C. is the maximum temperature to which such material should be heated.

The rate of cooling to Ar_1 appeared to have considerable influence upon the result ; when heated to 800° C. and higher, slow cooling tended to produce brittleness, a fact which probably explains some of those abnormal results often met with in works. In rolling small sections it is the practice in many works to stack the bars on the bank whilst still hot ; this means that they are either cooled very slowly through Ar_1, or are kept for a very long time between 500° and 600° C. The experiments point to this as being a dangerous temperature at which to heat the material.

The results obtained with larger sections of rolled steel containing ·2 per cent. Carbon, indicated 800° C. as the maximum temperature at which such material should be heated to obtain it in the most suitable condition to resist sudden shock. This temperature is slightly lower than the maximum obtained for the smaller bars.

The results of the experiments on forged bars of this steel, 6 inches in diameter, indicated 700° to 850° C. as the limits of temperature at which bars of this size should be heated to obtain the maximum resistance to sudden shock. At temperatures between 500° and 650° C. brittleness was produced in a very marked degree, *especially if followed by slow cooling.*

A second set of experiments, carried out with this size of bar, showed very clearly the effect of heating to temperatures between 500° and 1,000° C., and the results indicated 800° C. as the best temperature at which to heat bars of this size and composition.

Steel containing about ·3 or ·4 per cent. of Carbon in small rolled sections was improved as regards its shock-resisting qualities when heated to temperatures varying from 650° to 800° C., whether followed by slow or rapid cooling.

Heating between 500° and 600° C. did not produce the brittleness which occurs in ·2 Carbon steel when it is heated under similar conditions.

Large rolled bars of this material gave the best results after heating to temperatures of 700° to 800° C. When heated at 900° C. and higher, a pronounced brittleness developed. Slow cooling did not seem to be very injurious.

Forged bars of this steel, 6 inches in diameter, appeared to be brought into the best condition for resisting sudden shock by heating to temperatures between 700° and 760° C., followed either by slow or rapid cooling. The bar heated to 800° C. showed a marked falling off in the drop-test result, but as

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* *Iron and Steel Inst. Journ.*, 1903, No. 1.