CHAPTER III

THERMAL TREATMENT OF THE CEMENTED PRODUCTS

The cases in which the pieces of cemented steel are used directly, after cementation, without being subjected to further heat treatment, are very rare. It may, in fact, be held that the only such case is where the product, totally cemented, is to be fused in crucibles.

In all the other cases—and they are a very large majority—in which advantage is taken of the difference between the mechanical properties of the carburized zone and those of the nucleus, whose chemical composition has remained practically unchanged, the further operations of hardening, annealing and tempering are the only ones which develop to their full extent the different mechanical properties due to the different degrees of carburization of the steel.

The operations and the apparatus for heat treatment of the cemented products differ in absolutely no respect from the operations which are carried out and the apparatus which are commonly employed in technology for the heat treatment of any other kind of steel.

Thus, for heat treatment of the objects of cemented steel there are used the same heating furnaces (reverberatory, muffle, salt bath, lead bath, etc., heated with coke or gas or electricity) and the same means of cooling (water, salt solutions, oil, air currents, etc.) as are used for the heating and quenching of any object of homogeneous steel.

Apparatus or arrangements for the annealing are the usual ones (hearth or muffle furnaces) and also for the hardening (oil, lead, air baths, etc.). It would therefore be absolutely superfluous to give here detailed information as to the general technology of the heat treatment of the cemented pieces, as those directions form the subject of a large number of most valuable and complete works.[1] The hardening of steel objects superficially cemented differs from that of objects of homogeneous steel only as to the temperatures at which the quenching and the other heat treatments must be effected. This is owing to the fact that the temperatures at which the various heat treatments of a given steel must be effected depend on the concentration of the carbon in this steel; and therefore the rules for the heat treatment of homogeneous steel of a uniform carbon content can not, evidently, be applied

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[1] See, for example, the volume of Guillet, entitled: *Trempe, recuit, revenu;* that of Grenet: *Trempe, recuit, cémentation et conditions d'emploi des aciers* (Ch. Béranger, Paris, 1911); that of Reiser: *Das Härten des Stahles;* that of Lake: *Composition and Heat Treatment of Steel;* and many others.

directly to the heat treatments of a cemented piece which has, in its different parts, carbon contents varying between very wide limits.

It will therefore be well to indicate here how the rules which govern the temperatures adapted to heat treatment of the various types of homogeneous steels may most suitably be applied to the corresponding treatment of the cemented steels, so as to take the best possible advantage of the essential characteristic of the objects manufactured of such steels., *viz.*, the difference in carbon content from the periphery to the nucleus.

A steel object superficially cemented is essentially constituted of two parts, joined to each other by a transition region in which the composition and, therefore, the properties of the metal vary more or less gradually from those of the first to those of the second part. These two parts are the peripheral zone, constituted of a highly carburized steel, and the central part ("heart" or "nucleus"), constituted of a steel whose chemical composition has remained practically identical to that of the original material, while the structure and the mechanical properties have been more or less profoundly altered as the result of the long heating at a high temperature.[1]

It is clear that proper heat treatment of a partially cemented piece can never comprise less than two quenching operations, carried out at two different temperatures, so chosen as to confer the best mechanical properties upon the two constituent parts of the object.

The fundamental problem of the heat treatment of partially cemented pieces consists therefore in choosing the two temperatures in such a way that the useful effects of the two quenchings will be superimposed without harming each other.

Only when the mechanical properties of one of the two parts of the cemented piece have a greatly preponderant importance can it be desirable to limit the heat treatment to that one of the two quenchings which gives the best properties to that part. In such a case, we must be satisfied, as concerns the other part, with the properties which it assumes as the result of the single operation, even though these properties are not the best which a metal of that composition might possibly be given.

In the very large majority of cases we begin by carrying out a first quenching at a temperature sufficient to "regenerate" the steel of the "heart" of the cemented piece, which is always somewhat "burnt," trying to impart to this metal the maximum "tenacity."

This first quenching, called "regeneration quenching," is usually followed

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[1] It has already been pointed out how some experimenters have held that the increase in the brittleness of the steel of the "heart" of the cemented pieces could be attributed to other causes than to the long heating undergone by it during the cementation, *viz.*, to a modification in the chemical composition of the steel, and especially to an increase in its nitrogen content. It would seem, however, premature to accept such an hypothesis without further and more certain direct proofs.

by a "hardening quenching," carried out at a temperature lower than the first and designed to impart to the steel of the cemented zone maximum hardness compatible with the brittleness which can be tolerated in the cemented piece.

When the cemented piece is to resist only surface friction, but is not to be subjected to large bending forces nor to shock, the "regeneration quenching" may be omitted; while in cases in which it is not necessary to obtain a very great surface hardness, it is sometimes possible to do without a true hardening proper, merely making an attempt to carry out the single hardening (the "regeneration quenching") at the lowest possible temperature.

But the cases in which this second procedure may be considered advantageous are very rare, owing to the fact that the hardening quenching, always carried out at a relatively low temperature, does not carry with it any marked disadvantage.

On the contrary, the cases in which it is really desirable to follow the first procedure are quite frequent. This consists in the suppression of the regeneration quenching, owing to the fact that this being carried out generally at a high temperature results in marked deformation of the cemented piece. When this procedure is followed, however, it is necessary to carry out the cementation at not too high a temperature (between 850° and 950° C.) so as to avoid producing in the soft steel of the "nucleus" of the pieces such an excess of brittleness as could not be corrected by any tempering, but only by a true regeneration quenching proper.

As a typical example of the cases in which it is often expedient to suppress the regeneration quenching we may mention cups and rings for ball bearings, for which great deformations are more to be feared than the harmful effects of not obtaining maximum tenacity in the soft metal of the nucleus.

To indicate briefly the circumstances which must guide in choosing the heat treatment of partially cemented steel pieces, it is well to consider separately the various cases which present themselves in practice, according to the initial composition of the steel subjected to cementation.

When the cemented objects are made of ordinary carbon soft steel, which, as is well known, suffers more than any other the harmful effects of prolonged heating at a high temperature, the proper choice of the heat treatment has far greater importance than for the majority of other types of special "cementation" steels, for which one of the essential requirements is, usually, that of preserving maximum tenacity in the non-cemented parts.

When studying the heat treatment of a partially cemented piece of steel, we must always assume that the temperature at which the cementation has been carried out has been kept below the lowest limit of the crystallization of the most highly carburized zone of the steel under consideration; for, if this has not been the case, the partial fusion of the mixed crystals will have enormously accelerated the process of carburization at the periphery of the piece, and the formation of a cemented zone of cast iron proper will have rendered the cemented piece absolutely useless. This is the phenomenon which was observed many years back by Mannesmann, and which fixes absolutely the upper limit of temperature, above which partial cementation can not usefully be carried out. No heat treatment would "regenerate" a cemented piece made useless in this way. It is clear that both the metal constituting the "core" and the carburized zone of the cemented piece can not be "burnt" in the true sense of the word, but can only have undergone one of the two typical modifications in structure which manifest themselves when the temperature of heating is somewhat lower than the last transformation point of the steel or is comprised between this temperature and that of the "solidus" for the mixed crystals of the maximum carbon content contained in the steel under consideration.

Now, it is known that both in the one and the other of these two cases the "regeneration" of the steel can be effected by first making it undergo its complete transformation on cooling and then bringing it back for a short time to a temperature a little higher than that of its last transformation point on heating, to quench it, usually, directly from this temperature.

The necessity of making the steel undergo its complete transformation at least once, excludes the possibility of suitably regenerating and hardening the cemented piece without subjecting it to at least a second heating. It is, therefore, not possible to obtain a good product by simply allowing the cemented piece to cool to the temperature suitable for the regeneration hardening and quenching it directly at that temperature.

As to producing the transformation on cooling, it is clear that the simplest way would be to allow the cemented pieces to cool slowly from the temperature of cementation to a temperature markedly lower than that of the last point of transformation on cooling, and, eventually, even to ordinary temperature when the special form of the objects does not give cause for fear of cracking. We have seen, however, that while such a procedure is certainly better than any other in the case of objects of homogeneous steel, it presents in the case of the partially cemented objects the serious disadvantage of liquation of the ferrite and, perhaps, of the cementite during the slow cooling. These disadvantages, which have been discussed in great detail in the first part of this volume, make it preferable to first quench the steel at the temperature of cementation and then heat it very slowly up to the temperature of the regeneration. In this way the steel undergoes, during the part of the slow heating which precedes the first transformation point, a strong recovery which prepares it excellently for the regeneration. Only in the case in which the cementation is carried out at a very high temperature (1050°–1100° C.) is it desirable to let the cemented pieces cool to about 950°–980° before subjecting them to the first quenching. For the reasons already set forth, such a slow cooling can have no harmful effect, for it does not reach the temperature at which the processes of liquation of the ferrite or of the cementite can begin.

As to the temperatures at which the two quenchings—that "of regeneration" and that "of hardening"—must be carried out, these depend on the temperatures of the complete transformation of the two steels constituting the nucleus and the cemented zone. It is known, in fact, that the best results are obtained by carrying out the two quenchings at temperatures slightly above these two respective transformation points.

In an ordinary carbon soft steel, cemented under conditions such that the concentrations of the carbon shall be near 0.9% in the greater part of the carburized zone, the transformation of the soft metal of the "core" is completed at about 900°, while that of the greater part of the metal of the cemented zone is completed a little above 700° C.

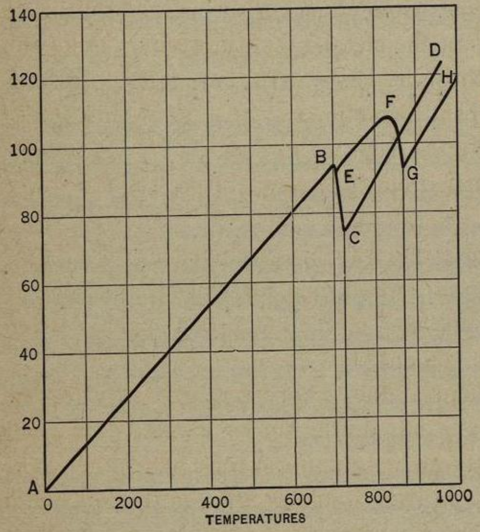

Fig. 152.

Fig. 152, taken from the volume of Grenet already cited, represents the curves of dilatation of the two parts of a cemented carbon soft steel. The position of the points *C* and *G*, which, as is well known, correspond to the end of the transformation during heating, fully confirms the data reported above.

Summarizing, then, what has been said in the pages which precede, the heat treatment best suited to an ordinary carbon soft steel, cemented under the usual conditions, is the following:

1. "Regenerating quenching," carried out at a temperature a little higher than 900° C.[1]

This first operation regenerates well the soft part of the cemented piece. Moreover, when in a part of the cemented zone the concentration of the carbon is higher than 0.9%, the heating to a temperature markedly higher than that of the segregation of the primary cementite produces a more or less complete solution of the laminæ of cementite, the permanence of which in the cemented and hardened zones is known to constitute one of the most important causes of brittleness. Moreover, even in the case in which the concentration of the carbon in the cemented zone does not exceed 0.9%, the regeneration quenching acts efficiently as a means of rendering more uniform and gradual the variations in the concentration of the carbon between the various points of the carburized zone, throughout the whole extent of which the steel, at the high temperature at which the quenching is effected, is present in the state of stable mixed crystals.

It sometimes happens, either owing to the special chemical composition of the steel or to the too large dimensions of the object being treated, that the first regeneration quenching does not produce all the effect of which it is capable, either on the properties of the metal constituting the core of the cemented piece or on those of the carburized zone. In these cases it is useful to repeat the quenching a second and sometimes even a third time under the same conditions.

2. "Hardening quenching" carried out at a temperature slightly lower than 800° C.[1]

This second quenching can, in a certain way, be considered also as a regeneration quenching of the steel of the carburized zone, for which the heating at 900° C. (necessary for the "regeneration" of the metal of the core) is too high, in relation to its high carbon content.

The cemented piece must be kept at the temperature necessary for the hardening quenching (about 800° C.) only during the time strictly sufficient to insure that this temperature is thoroughly uniform throughout the whole cemented zone, for too prolonged a heating would produce in the soft metal constituting the core of the piece those characteristic phenomena of crystallization (accompanied by great increase in brittleness) which, as is known, show themselves in all carbon steels heated for a long time at a temperature slightly lower than that at which the transformation on heating ends.

Moreover, if the cemented zone is markedly hyper-eutectic, a prolonged heating at about 800° C. results in agglomerating into masses of considerable dimensions that portion of the small elements of cementite (separated, during the second heating, from the mixed crystals "fixed" by the first "regeneration quenching") which remain after the mixed crystals have become saturated at 800°. As is known, such a process also gives rise to a great increase in the brittleness of the cemented zone and favors the phenomena of exfoliation.

In some cases it may be desirable, for reasons of simplicity and of rapidity,

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[1] It is often advisable to considerably exceed this temperature and to quench from 1000°, since the transformation into γ iron, which destroys the grain, is subject to retardations like all polymorphic transformations. It is on the same principle that Osmond and Cartaud (*Rev. de Mét.*, III, 658, 1896) state that to transform a primitive crystal of α iron into small grains it is necessary to exceed the temperature of the point A_3 "sufficiently and for a sufficiently long time." Industrial practise confirms this theoretical remark. [Note in French Translation—by A. Portevin.]

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[1] A fact which seems to have been remarked by no one, and which we have confirmed on steel cemented at 1000° (in a mixture of wood charcoal and barium carbonate), is the increase of brittleness of the core caused by quenching at low temperature after cementation. [Note in French Translation—by A. Portevin.]

to simplify the complete heat treatment to which I have referred. For cemented carbon steels, these simplified treatments are summarized and concreted by Grenet[1] as follows:

Treatment (*a*)—Hardening of the pieces as soon as they are removed from the cementation chambers. This treatment can be usefully applied only to pieces designed to be subjected only to surface friction and not to forces capable of producing fracture or exfoliation.

It is necessary that the pieces should be removed from the cementation chamber (usually, the boxes) while they are still hot (above 800° C.) and quenched immediately.

This process, which has the advantage of being rapid and of imparting great hardness to the surface of the cemented pieces, is not advisable, for it does not permit of effecting the quenching at a well-defined temperature, and regenerates neither the cemented zone nor the core of the pieces.

Treatment (*b*)—After the cementation the piece is allowed to cool, then heated to 950° and quenched in water.

For the reasons which we have already seen, such a treatment acts efficiently in regenerating the soft metal constituting the core of the cemented pieces, imparting to this metal the maximum tenacity of which it is capable, but it certainly is not the one best adapted for the cemented zone, which should be hardened at a much lower temperature.

As to the way of practically conducting the complete thermal treatment, with double quenching, Grenet makes some observations which it may be well to summarize here briefly.

First of all, in the execution of the first "regeneration quenching," which it would be advisable to carry out at 950°, the melting temperature of barium chloride, it is well to remove the piece from the water when its red color is seen to disappear, and this because the rapid cooling of the piece to the temperature of the water (usually below 20° C.) predisposes it to cracking and exfoliation during the succeeding heating for the "hardening quenching." On the other hand, the hardening, even when interrupted in the manner indicated above, is no less efficacious in the regeneration of the soft metal of the core than is the complete quenching, for when the red color of the piece totally disappears the temperature has certainly fallen below 600° C., that is, much below the temperature at which the transformation on cooling is totally effected. Moreover, the efficacy of the interruption of the process of rapid cooling in the water, in diminishing the probability of the formation of cracks during the succeeding heating, is evident even if this interruption takes place at a temperature little higher than 200° C. It is therefore clear that no special skill is necessary to have the interruption of the hardening, executed as above described, give all the useful effects of which it is capable.

Effects analogous to those of the interruption of the hardening can be obtained by the various well-known modifications of the quenching adapted to "deadening" its effects; as, for example, by quenching the piece in oil or in hot water.

The necessity of regenerating the metal of the core of cemented objects makes it very harmful to apply the partial quenching, which is often successfully used on homogeneous steel, when it is desired to harden only a part of it. It is clear, in fact, that if the hardening is limited to a part of the cemented object, the metal constituting the other part, always considerably altered by the long heating which accompanies the cementation, will remain brittle.

The partial hardening can be applied in the second part of the complete, double quenching, thermal treatment. In this case, in fact, the metal is already completely regenerated by the regeneration quenching effected on the whole mass of the cemented object, and the heating at 800° C. which precedes the hardening quenching, being conducted rapidly, does not produce practically appreciable alterations, not even in the part of the metal which does not undergo the second hardening. This last observation holds for those parts of the metal which it is desired to keep soft (and therefore not to immerse in the hardening bath) which could not have been protected from the second heating owing to their closeness to the parts to which it is desired to impart the maximum hardness.

When the simplified thermal treatment which we have called "*treatment* (*b*)" (simple quenching at 950°) is applied, Grenet advises to heat the whole of the cemented piece to the quenching temperature, then immersing in the hardening bath only the part which is to be hardened. Grenet advises, in this case, to immerse the whole piece in the water and to remove the part which is not to be hardened as soon as the red color is seen to disappear.

Experience with this last procedure, constituting, as is clear, a special application of the so-called "recovery by heat proper," has showed me that in the majority of cases great practice is necessary to obtain constant results with precision.

The difficulty in the practical application of the processes of partial quenching to cemented pieces puts still more clearly in evidence the practical importance of the methods for the "local protection" of the pieces subjected to cementation.

To show what may be the effects of the prolonged heating which accompanies the cementation, and the efficacy of the regeneration quenching on cemented ordinary carbon soft steels, we will cite some numerical data from the article by Guillet in the *Génie Civil*, already frequently referred to.

The following table shows well the increase in the brittleness of an extra-soft carbon steel as the result of the prolonged heating. In all seven of the experiments to which the numbers of the table refer, the heating was conducted by keeping the temperature constant for eight hours. The resistance to shock was determined on a Fremont test piece 8 × 10 mm.

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[1] *Trempe, recuit, cémentation et conditions d'emploi des aciers* (Béranger, Paris, 1911).

From the data reported, it follows clearly that the increase in brittleness of the steel examined, due to rise in temperature of the heating, becomes a maximum for just the interval of temperature (850°–1000° C.) within which the increase in the velocity of the cementation due to a given increase in the temperature is a maximum.

Temperature at which the heating was effected	Resistance to shock (kilogram-meters)	Temperature at which the heating was effected	Resistance to shock (kilogram-meters)
800° C.	26	1000° C.	4
850° C.	28	1050° C.	3
900° C.	15	1100° C.	4
950° C.	12		

The increase in the brittleness of a carbon soft steel due to increase in the temperature of the heating, however, manifests itself to a degree varying within wide limits for even small variations in the composition of the steel. It would certainly be most useful to have precise data on the relations which connect the two variables.

From a series of experiments carried out by Guillet, it seems to be proved that the effects produced by cementation (carried out with cements having carbon monoxide as base and free from cyanides) on the mechanical properties of the soft metal constituting the core of the cemented pieces are identical to those produced by heating in a neutral medium, at the same temperature and for the same time. These effects would therefore be due exclusively to the action of the heat treatment which accompanies the cementation.

Other experiments carried out by Guillet with nitrogenous cements gave extremely irregular results, from which it is difficult to draw conclusions as to an eventual chemical action exercised by the cement on the metal of the core of the cemented pieces.

As an example of the effects which the regeneration quenching may exercise on the properties of the soft carbon steel constituting the core of the cemented pieces, I report in the following table some results of shock tests, also taken from the memoir of Guillet, cited above.

No. of the extra-soft steel used	Original bar heated at 925° C. and allowed to cool in the air (kilogram-meters)	Original bar quenched at 925° C. in water at 20° C. (kilogram-meters)	Bar cemented for 4 hours at 1000° C., not quenched (kilogram-meters)	Bar cemented for 4 hours at 1000° C. and quenched at 1025° C. in water at 20° C. (kilogram-meters)
1st type......	28	32	10	30
2nd type......	32	32	12	28
3rd type......	28	34	9	3
4th type......	33.4	34.5	31	33

The shock tests were made on test pieces of the Mesnager type, obtained *wholly* from the core of the bars. The last is a condition absolutely essential if the results of the shock tests are to represent the true brittleness of the metal constituting the core of the cemented pieces.

The numbers contained in the table reproduced above, while showing, in general, the regeneration quenching to be an efficient means of diminishing the brittleness of a carbon soft steel heated for a long time to a high temperature, also show that the extent of the effects which can be obtained by such a heat treatment may vary between very wide limits with variation in the composition of the steel used.

As a summary example of the specific effects of the various quenchings on the mechanical properties of the two parts of a piece made of an ordinary cemented extra soft steel, we have the following table, also taken from the memoir of Guillet which has been already cited several times:

Treatments	Resistance of core to shock in kg.-m. (Mesnager test piece)	Surface hardness determined by Shore method		
		Mean	Minimum	Maximum
Non-cemented steel, heated at 925° C. and cooled in air.	20.6	....	....	....
Non-cemented steel, quenched at 925° C. in water.	23.8	....	....	....
Steel cemented at 1000° C. for 1.2 mm. and cooled slowly.	13.5	38.50	38	40
Steel cemented at 1000° C. for 1.2 mm. and quenched at 1000° in water.	23.2	79.80	78	83
Steel cemented at 1000° C. for 1.2 mm. and quenched twice in water, at 1000° C. and at 750° C.	25.5	84.0	81	88

The most easily recognizable effect of the regeneration quenching on the core of the cemented pieces is the change in the appearance of the surface of fracture. This surface, which before the quenching has a "granular" appearance, assumes a "fibrous structure" as the effect of the quenching.

The effects produced by a given series of heat treatments on the mechanical properties of an ordinary carbon soft steel vary between very wide limits with variation in the composition of the steel subjected to the treatment. The experimental data at present known do not permit of expressing in numbers the relations between these variations. As a general rule it may be held that for a cemented soft steel the brittleness produced by the prolonged heating is the greater, and the efficacy of the quenching the smaller, the higher the initial concentration of the carbon. Save for few exceptions (as, for example, the manufacture of matrices, etc.), an ordinary carbon soft steel designed for the manufacture of cemented mechanical pieces must not contain more than 0.2 percent of carbon. This limit can be exceeded only for some special steels; for example, the nickel steels.

A too high content of manganese (0.5–0.7 %) or of silicon (more than

0.3 %) also increases the brittleness produced by the prolonged heating during cementation, and diminishes the efficacy of the regeneration quenching.

All the data just reported hold for the case where the steel used for cementation is an ordinary soft carbon steel.

The use of some well-defined types of special steels permits of simplifying the thermal treatment which is to follow the cementation, of greatly increasing its efficacy and of rendering its results considerably more certain.

The special steels most frequently used for cementation are the soft nickel steels. The superiority of the soft nickel steels over the ordinary carbon steel, for this purpose, is due to the fact that the increased brittleness produced by a definite heating at a high temperature is considerably less for the steels of the first type than for those of the second. This fact is seen most clearly from the numbers contained in the following table, also taken from the memoir of Guillet which has been already several times cited.

Although Guillet does not indicate the temperature at which the heating was carried out and these data can, therefore, be considered only as to their relative value, they show very clearly the fact set forth above. This is confirmed by the observation, many times repeated by a large number of experimenters, that, if the length and the temperature of heating are equal, the pearlite remains considerably finer, more uniformly distributed, and much more subdivided, in a nickel steel than in a carbon steel.

Length of heating	Resistance to shock	
	Ordinary extra-soft steel	Extra-soft steel with 2 % of nickel
Normal heating	20 kilogram-meters	60 kilogram-meters (not broken)
Four hours	4.5 kilogram-meters	60 kilogram-meters (not broken)
Six hours	4.0 kilogram-meters	60 kilogram-meters (not broken)

Besides this, we have seen that, with the same heat treatment, in partially cemented nickel steels, those phenomena of the liquation of the cementite and of the ferrite which constitute the principal cause of the exfoliation of the cemented and hardened pieces make themselves felt to a considerably less degree than in ordinary carbon steels.

It is indeed true that together with these marked advantages the nickel cementation steels present some disadvantages, but these disadvantages, which can for the most part also be eliminated by proper conduct of the cementation, are not of great practical importance and are almost always largely compensated by the advantages already referred to.

One of the disadvantages most frequently attributed to the nickel cementation steels is the greater slowness with which the cementation proceeds in them. Now, while this fact may manifest itself with the use of certain

cements it is, however, quite certain, as was shown clearly in the first part of this volume, that this does not manifest itself when the mixed cements with carbon monoxide as base are used; with these the cementation of the nickel steels is effected with the same rapidity as that of the ordinary soft carbon steels.

Greater practical importance must be attached to the other disadvantage, brought out by many investigators, of the lesser hardness which, with the same treatment, is possessed by the carburized zones in nickel steels as compared with the carburized zones of ordinary carbon steels under identical conditions. This fact is due not only to the different effects produced by a different quenching on the steels of the two types, but also to the smaller concentration which (especially for steels containing more than 3% of nickel) the carbon attains in some cases in the cemented zones of the nickel steels as compared with that in the ordinary soft carbon steels cemented under identical conditions.[1] It is easy, however, to eliminate this disadvantage with certainty by making use of one of the numerous means described in the first part of this volume for raising the concentration of the carbon in the cemented zones.

As to the various other disadvantages attributed to the use of soft nickel steels as cementation steels, such as the tendency to the formation of flaws difficult to eliminate, the great heterogeneity, etc., they may to-day be considered as totally eliminated, thanks to the great perfection attained in the manufacture and in the preliminary treatment of the special steels of every kind.

We will now consider the heat treatments most suitable for developing the useful properties characteristic of the nickel steels when used for cementation.

To treat of this subject with sufficient clearness, it is necessary to subdivide the soft nickel steels used for cementation into two groups; the first of these includes the steels containing less than 4% of nickel, while in the second the nickel content exceeds that value and may, in practice, rise as high as 6–7%. We will assume the heat treatment of homogeneous nickel steels as being known and will give only the special rules which hold for the thermal treatment of these steels after having been cemented.

1. Among the cementation nickel steels belonging to the first group, the one most frequently used is that with 2% of nickel. This steel cements in almost exactly the same way as the carbon steel, and furnishes cemented zones capable of assuming great hardness on quenching in water.

The fact that the brittleness of the core of the cemented pieces manufactured of this steel does not increase much as the result of the heat treatment which accompanies the cementation, together with the fact that the temperature of transformation, during heating, of the metal constituting this core is

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[1] See p. 140.

considerably lower than that of soft carbon steels, makes it possible to produce regeneration of the core perfectly well, in the case with which we are dealing, by quenching at 850° C., in water or in oil. But since the cemented zone of the steel with 2% of nickel can be hardened at a temperature markedly higher than the normal quenching temperature of a carbon steel of equal carbon content, it follows that the regeneration hardening carried out under the conditions just indicated is amply sufficient, in the majority of cases, as a hardening quenching also.

It is seen, therefore, that in case the cemented and hardened piece is not to be subjected to exceptional stress, the heat treatment of the cemented pieces is markedly simplified by the use of the soft steel with 2% of nickel.

But, even for the steel with 2% of nickel, the single quenching carried out under the conditions as indicated is only a simplified treatment, whose practical usefulness consists especially in shortening the operations and in diminishing the causes of deformation of the pieces. Even for these steels considerably better results are obtained by separating the two quenchings of "regeneration" and of "hardening," and by effecting each one of them at the most suitable temperature, fixed by the transformation points of the metal of the core and of that of the carburized zone.

It is well known that the point of transformation on heating and that on cooling, points which for carbon steels are quite close to each other, are farther removed from each other in nickel steels the higher the nickel content. This fact, together with the smaller velocity with which the variations in the concentration between the various points in the solid solutions[1] are effected in the nickel steels, leads to raising somewhat the temperature of the regeneration quenching.

The complete thermal treatment of a cemented piece of soft steel with 2% of nickel is therefore as follows:

(*a*) Quenching in water, from 960°–980° C. The piece is removed from the water when it ceases to be red.

(*b*) Quenching in water from about 740°–770° C.

To show the efficacy of this heat treatment, the numerical data in the accompanying tables, also taken from the memoir of Guillet previously cited, are of value.

The data in Table *A* show the efficacy of the regeneration quenching effected at about 1000° C. (cases 4 and 5).

The data in Table *B*, next, show the advantage of carrying out the hardening quenching at a lower temperature (about 750° C.).

The cemented steels containing a proportion of nickel somewhat higher, but not more than 3·70–4%, are treated in an entirely analogous way.

2. Soft nickel steels of the second group, containing about 6–7% of nickel, are characterized by the fact that after the cementation the point of transformation of the metal on cooling, constituting the carburized zone, is lowered almost to the ordinary temperature. We have described, in the first part of this volume, the interesting observations made by Guillet on the phenomena which take place in the cementation of these steels.

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[1] Of this fact we have already seen a proof in the lesser extent of the phenomena of liquation.

TABLE *A*

No.	Treatment	Resistance to shock (kilogram-meters)
1	Steel with 2% of Ni and 0.1% of C heated at 925° C., allowed to cool in the air	33·4
2	The same steel, quenched in water at 925° C.	34·5
3	The same: cemented at 1000° C. for 1.2 mm. and slowly cooled	31.0
4	The same: cemented in an identical manner and quenched in water at 1000° C.	33·5
5	The same: cemented in an identical manner and quenched twice in water at 1000° C. and at 750° C.	36.0
6	The same: cemented in an identical manner and quenched in water at 750° C.	32.0

TABLE *B*

No.	Treatment	Hardness numbers		
		Mean	Minimum	Maximum
1	Cemented pieces, not quenched	39·37	39	40
2	Cemented pieces, quenched at 1000° C.	78.05	69	84
3	Cemented pieces, quenched at 750° C.	86.56	85	88

For the same reasons already indicated in connection with the steels of the preceding group, and especially on account of the greater slowness with which the concentration equilibrium of the mixed crystals establishes itself, it is necessary, in order to obtain a really efficient regeneration of the metal of the core, to carry out the regeneration quenching at a temperature markedly higher than that which would be defined by the end of the transformation on heating. The most suitable temperature for the regeneration quenching of a cemented steel with 6% of nickel is, according to Guillet, 850° C., while for the hardening quenching Guillet indicates 675° C. as the most suitable temperature.

In the following table, also taken from Guillet, are collected some results of hardness determinations with the Shore apparatus on steel with 6% of nickel, cemented and quenched in various ways:

No.	Treatment	Hardness numbers		
		Mean	Minimum	Maximum
1	Cemented pieces, not quenched	35.6	34	38
2	Cemented pieces, quenched at 700° C.	68.7	60	80
3	Cemented pieces, heated at 750° C. and quenched at 650° C.	62.7	60	70

As is seen, the results oscillate between quite wide limits, but for these high nickel steels the hardness of the cemented and quenched zone does not reach as high values as for ordinary steels. This last fact is probably due to their tendency, already noted, to retain considerable proportions of γ-iron, as well as to the effect of not very energetic quenching. When it is not necessary to impart very high tenacity to the metal of the core, and great hardness in the cemented zone is not to be obtained, the cemented objects made of soft steel with 7% nickel can simply be allowed to cool slowly after the cementation, as practised by Guillet and described already in the first part of this volume. The principal advantage which this presents consists in its great simplicity, and in the fact that it permits of avoiding the deformations which always accompany the quenching of any steel object.

The following table contains the results of some hardness determinations made by Guillet (with the Shore apparatus) on a steel containing 7% nickel and 0.12% of carbon, cemented to a depth of 1 mm. and not hardened by quenching.

The determinations were repeated after having removed successively three layers of the cemented zone, each 0.2 mm. thick; there was thus obtained an approximate indication of the variations in the hardness of the various successive layers of the cemented zone:

No.	Treatment		Hardness numbers (Shore)		
			Mean	Minimum	Maximum
1	Piece cemented to 1 mm., not quenched		18.5	17	21
2	Piece cemented to 1 mm., not quenched, from which is removed a layer having a thickness of —	0.2 mm.	26.5	26	27
3		0.4 mm.	24.5	24	25
4		0.6 mm.	20.2	20	21

The treatment just indicated presents some disadvantages, however. The first of these consists in the small hardness imparted to the cemented zone; this is seen clearly in the last table. The second disadvantage lies in the fact that the core of the cemented pieces is not regenerated.

This disadvantage can be avoided in part by subjecting the cemented pieces to a second heating followed by a cooling in the air; in this case, however, the process loses its simplicity, although retaining the value of avoiding the deformation of the pieces.

The last disadvantage of the method with which we are dealing is the necessity of using steels of very high cost.

When it is necessary to obtain cemented zones capable of assuming great hardness without excessively-energetic quenching, it is quite well to use cemented soft steels containing small quantities of chromium, varying, in general, from 0.6%. to 1.3 %. The presence of such quantities of chromium does not markedly modify the thermal transformations of the steel, so that the heat treatment of cemented pieces made of chromium soft steels can be carried out by applying the rules for ordinary carbon steels.

It is well, however, to remember that the presence of the chromium tends to render more appreciable the harmful effects of the prolonged heating on the metal in the core of the cemented pieces; this renders the regeneration quenching indispensable for cemented pieces of chromium soft steel.

In the table following (Guillet) are collected some data obtained by the various heat treatments of soft chromium steels.

The property of these steels of assuming great hardness in the cemented parts as the result of even relatively mild quenching renders them very useful for the manufacture of pieces which, after cementation, are to be subjected only to quenching in oil or in boiling salt water, so as to avoid deformations as much as possible.

No.	Heat treatment	Composition of the steel	
		Cr = 0.70% C = 0.05%	Cr = 1.20% C = 0.05%
1	Resistance of annealed metal to shock	32 kg.	25 kg.
2	Resistance of quenched metal	22 kg.	15 kg.
3	Resistance of metal heated four hours at 1000° C.	6 kg.	5 kg.
4	Resistance of metal after double quenching	26 kg.	20 kg.

The chromium-nickel soft steels are at present used on a very large scale as cementation steels for similar purposes. The thermal treatment of cemented pieces made of these steels does not differ appreciably from that described for the nickel steels of equal nickel content.

The presence of nickel (usually in proportions varying from 2 to 3%) together with the chromium renders less marked the increase in brittleness of the core due to the heating which accompanies the cementation, while it no longer appreciably diminishes the hardness which a definite quenching can impart to the cemented zone.

The consequence of the first fact is that it is possible to use without disadvantage chromium-nickel steels for cementation having an initial carbon content up to 0.3%, which is higher than the maximum allowed in the other steels used. The second fact renders these steels, for the reasons to which I referred in speaking of the chromium steels, especially adapted to the manufacture of pieces subjected to strong shocks and which must not be appreciably deformed as the result of the quenching; such, for example, are certain gear-wheels.

We have also seen (see p. 334) that these steels cement more rapidly and better than carbon steels.

There are sometimes used cementation steels containing (usually together with chromium and nickel) small quantities of tungsten, molybdenum, and vanadium. The heat treatment of these steels does not differ markedly from that for steels containing equal amounts of the other elements (C, Cr, Ni).

Moreover, it has not yet been proved with certainty that the advantages conferred by these elements upon the characteristic properties of a cemented steel justify their high cost.

For the process of tempering (rarely applied to cemented steel objects) and of annealing, the same rules hold for cemented steels as are followed for homogeneous steels.

We have already seen, in the first part of this volume and in Chapter II of the second, what useful practical results can be obtained by subjecting the cemented steel objects to a heating, carried out under definite conditions, adapted to facilitating the processes of "equalization" of the concentration of the carbon between the successive layers of the cemented zone. These processes are to be considered rather as true chemical processes, due to the intervention of carbon monoxide, than as simple heat treatments.

There remains to be considered briefly a phenomenon which almost constantly accompanies the hardening of every kind of steel pieces, but which in the case of the quenching of cemented pieces assumes special importance, *viz.*, the phenomenon of the deformation of the pieces.

The simple cementation itself causes deformation of the pieces, especially if it is carried out at a high temperature and if the pieces are charged into the cementation chamber without being well supported at every point, by the cement or by the other pieces or by special supports. These deformations are very easily accentuated in the successive quenchings. This fact and also the fact that the changes in volume which hardening produces in the metal of the core and in that of the cemented zone are not identical especially predispose the cemented pieces to deformation on hardening.

For these reasons, and also owing to the ease with which the cemented and hardened zones break on attempting to straighten out the deformed pieces, the hardening operation is particularly delicate and difficult.

The deformations during cementation are especially marked in pieces which have previously undergone extended mechanical treatment (drawing, rolling, forging, etc.). For such it is well to have a heating and a straightening out operation precede the cementation; this is much easier when done on pieces which have not been cemented.

When the cemented pieces are to be subjected to double quenching, it is very desirable to straighten them out accurately and almost completely after the first quenching (*regeneration*) when, as we have seen, they are not brittle. Moreover, at this point of the treatment even a considerable softening of the metal does not harm the final result of the complete thermal treatment, so that, especially in the cases in which the deformations are very strong, the pieces which are to be straightened out can be heated even up to dark redness. Then the pieces, almost perfectly straightened, have to undergo only the second quenching (*hardening*), which deforms them but slightly. In this way, the completely hardened, and therefore more brittle, pieces have then to submit to only small stresses to be completely straightened.

This last straightening must be carried out with considerably more care than is necessary in the case in which hardened pieces of homogenous steel are to be straightened out. During this operation it is sometimes expedient to heat the pieces to about 80°–100° C. to diminish their brittleness.

The procedures and the apparatus which are used for straightening the cemented and hardened pieces do not differ in any respect from those which are used in all the other ordinary cases.

It is well to remember, however, that in the straightening of cemented and hardened pieces, especially if done cold and after the "hardening quenching," it is necessary, as far as possible, to avoid using forces which tend to elongate the cemented zone, as the metal which constitutes the latter can undergo practically no elongation after the hardening, and therefore breaks away with the greatest ease under such forces. To avoid this, it may sometimes be necessary (as happens, for example, in the case of cemented armor plate) to deform the piece artificially before the hardening, so as to be sure that after the hardening there shall remain a deformation in exactly the desired direction, so that the straightening, when cold, can be carried out without subjecting the cemented zone to *tensile* stresses.

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[1] However, practise has shown that following the hardening quenching by a light tempering diminishes the brittleness of the teeth of gear wheels cemented by a mixture of wood charcoal and barium carbonate. The tempering diminishes the internal strains produced by quenching in the cemented layer where the carbon content varies rapidly. [Note in French Translation—by A. Portevin.]