scale will be reduced by placing the gear out of doors, and allowing some drainage, through or off the ground, which will quickly convey away any escaping liquid. It would be an advantage if a liquid could be produced having the insulating and preservative qualities of oil, but less explosive than the mineral oils used at present. Fig. 6 is an illustration of a construction of this kind now in experimental service in Bradford, and Figs. 7 and 8 show a possible development of the type as it might be applied in the future to a large super-power station. The entire circuit-breaker is the removable portion. It will be raised as a whole by crane or a truck for inspection and adjustment, when these become necessary after it has opened on a short-circuit. If two alternative sets of 'bus-bars are used, the change-over from one to the other will be effected by lifting the removable portion clear of the isolating contacts, giving it a turn through a suitable angle, and then lowering it into its new position. The design must comply with the fundamental requirement that all the conductors shall be metal-clad and immersed when alive. Further, in switchgear of this type each phase must be separately housed by the metal frame-work; the large metal-clad gear already working at Dalmarnock, Barking, and other similar power stations, is actually constructed on these lines. In addition, the arrangement now illustrated is such that there is no place where conductors at the potential of one set of 'bus-bars are contained in the same chamber as conductors connected to the other set of 'bus-bars; in other words, the 'bus-bars and the individual phases are completely surrounded by enclosures of the earthed metal type.

Although the call of economy is unrelenting, it is not only required in the initial cost; it must equally be secured in maintenance and running costs, and in the elimination of housing, of expensive protection against fire and other hazards, and of risks to life. The mechanical construction of the moving parts, the tripping mechanism, and the weatherproof qualities of switchgear are becoming more and more perfect as a result of lengthening experience in the design and manufacture or both indoor and outdoor types, so that the future should see a stage of development in these directions that will give practically entire immunity from mechanical failure. Complete immersion in oil protects the insulation, and research will lead to a perfect understanding of the exact clearances and other features required under the practically stable conditions of oil immersion. The case is entirely different for conductors and insulators exposed in air, because the dielectric properties of air are changeable, and this variability in the insulating value of the air clearances, together with the access of dirt and other extraneous interference, is always apt to weaken the insulation, and thus to lead to breakdown. There must, however, be no breakdown of gear which is itself to be a protection against breakdown and interruption of supply, and the 'bus-bars, the current transformers, and all the component parts of the gear, including the insulators and the conductors of the circuit-breaker itself, must be enclosed for protection against the elements. It is by working along the lines that have been indicated throughout this paper that security of life and property, as well as safety, simplicity, and continuity of operation, will most certainly be ensured.

I wish to acknowledge co-operation on this subject by my company, Messrs. A. Reyrolle and Company, Limited, and assistance in compiling this brief paper from members of its staff.

THE WORK-HARDENING OF STEEL BY ABRASION.*

By EDWARD G. HERBERT, B.Sc., M.I.Mech.E.

THE present work describes an investigation into the hardness induced by severe abrasion in locomotive tyres and rails, and in hardened steel gears and cams from motor-cars. The hardness induced by wear is compared with the "maximum induced hardness" measured by a recently developed test made with the pendulum hardness tester. A somewhat similar comparison between the hardness induced by lathe tools in the process of cutting certain steels, and the hardness induced by the pendulum in the same steels, has been previously described by the author.

I.—THE MEASUREMENT OF WORK-HARDENING CAPACITY.

The Time Test.—For the purpose of measuring the original hardness of the subjects investigated and for measuring the hardness of the worn surfaces, the time test of the pendulum hardness tester was used. The pendulum and the time test have been described by Benedicks and Christiansen.† Briefly, the pendulum, weighing 4 kg., is placed on the specimen, a hard sphere 1 mm. in diameter, acting as a pivot, and is caused to oscillate through a small arc. The time period of oscillation, taken with a stop-watch, is a measure of the size of the indentation, and thus of the hardness of the specimen.

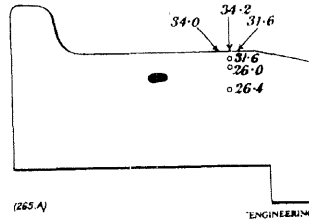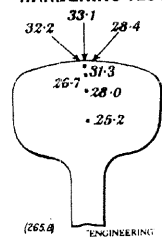Fig.1. SECTION OF LOCOMOTIVE TYRE TESTED FOR HARDNESS AND WORK-HARDENING.

Fig.3. TIME-WORK-HARDENING TEST.

Passes of Ball :	0.	2.	4.
Time Hardness ...	25·8	35·5	35·4

The Time-Work-Hardening Test.—The work-hardening capacity of the metal is measured by a succession of time tests on the same spot, each test being followed by a process of rolling effected by tilting the pendulum to the right, to the left, and back to the vertical position. This process rolls out the original circular impression into an elongated form (Fig. 8), and work-hardens the metal, the succeeding time test, made in the centre of the rolled surface, serving to measure the hardness thus induced. There is thus obtained a series of time-hardness numbers, of which the first gives the original hardness, the second the hardness induced by two passes of the ball, the third the hardness due to four passes, and so forth. The hardness always rises to a maximum—"the maximum induced hardness"—and then declines with further rolling. Thus the time-work-hardening test measures two distinct properties of the metal, its "original hardness" and its "maximum induced hardness." The former corresponds with the hardness measured by the Brinell and other hardness tests. The latter depends on and measures the capacity of the metal for hardening by cold-work.

Time-hardness numbers are convertible into approximate Brinell numbers, and for the convenience of those more familiar with the Brinell scale, the equivalent Brinell numbers are given throughout the paper. The conversion is effected by the following formulæ which apply to steel :—

$$B = 0.36T^2, \text{ when T is 28 or less };$$
$$B = 10T, \text{ when T is above 28 };$$
$$B = 13-5D \text{ on hard steel };$$

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* Paper read before the Iron and Steel Institute, Glasgow, on September 22, 1927. Abridged.

† *Journal of the Iron and Steel Institute*, 1924, No. II, page 219.

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where B is the Brinell number, T the time-hardness number obtained with the 1-mm. steel ball in the pendulum, and D the time-hardness number given by the pendulum and 1-mm. diamond sphere. In Table II, a number of typical steels have been placed in the order of their original hardness, the maximum induced hardness being given together with the approximate Brinell hardness corresponding to each. Among the unhardened steels, the highest induced hardness was given by manganese steel which was originally very soft, whereas the mild steel which was originally harder had a much lower induced hardness. The hardest stainless steel (C) showed only a moderate increase of hardness, stainless steels A and B, which were originally much softer than C, becoming considerably harder as the result of rolling.

TABLE II.—*Hardness and " Maximum Induced Hardness" of Various Steels.*

	Original Hardness.		Maximum Induced Hardness.	
	Time.	Brinell.	Time.	Brinell.
Stainless steel A	18·0	116	44·0	440
Stainless iron	19·6	138	32·5	325
Stainless steel B	19·7	140	52·9	529
Manganese steel	21·0	158	57·2	572
Mild steel	21·2	162	31·5	315
Stainless steel C	27·5	270	36·5	365
Hard nickel steel	54·5	735	88·7	1,197
Hard carbon steel	55·4	749	71·4	964

The two hardened steels were tested with the diamond in order to eliminate any effects due to superhardening of the ball, and the Brinell conversion factor 13·5 was used. The hard nickel steel, though originally less hard than the hard carbon steel, showed a much greater increase of hardness. Its maximum induced hardness was equivalent to nearly 1,200 Brinell, a degree of hardness which has rarely been exceeded in steel. The fact that articles of very hard steel can be superhardened by working was discovered by means of the pendulum work-hardening tests, and independently by Hultgren, who turned it to practical account in the superhardening of steel balls. It is perhaps not sufficiently recognised that this effect normally occurs when hard steel articles are subjected to severe abrasion. This subject is dealt with in the next section.

The process of work-hardening in unhardened metals has been studied in some detail, and is known to be accompanied by slipping of the metal along definite crystallographic planes. Whether the superhardening which takes place in hardened steels is strictly analogous is not known. Recent experiments suggest that it may be accompanied by a consolidation of the metal—an actual decrease of volume—but this is not yet certain. As it is proposed to consider the process only in relation to its practical effects, it will suffice to say here that the superhardening of hard steel is as considerable in amount, as important in its practical results, and as easily measured as the work-hardening of the softer metals.

II.—WORK-HARDENING OF METALS IN SERVICE.

A. *Work-Hardening of Railway Tyres and Rails.*—An investigation was made into the degree of work-hardening that had occurred in actual service in a series of locomotive tyres and rails which had been in long use, and had been discarded as worn out. Fig. 1 shows a section through a worn locomotive tyre which was tested for hardness with the pendulum time test in the positions shown. The hardness of the body of the tyre was 26·4 (264 Brinell), and 1·6 mm. from the surface 31·6 (316 Brinell). The highest hardness on the actual worn surface was 34·2 (342 Brinell). A time-work-hardening test was made on a part of the section which had not been hardened by service conditions in the position indicated by the elliptical impression (Fig. 1) with the following results :—

Passes of Ball :	0.	2.	4.	6.
Time hardness	26·2	31·7	32·0	32·0

The original hardness 26·2 increased to a maximum 32 as a result of rolling four times. It appears from Fig. 1 that the hardness induced by wear was rather higher than the maximum that could be induced by rolling.

Two series of time tests were made on another worn tyre. In each case there was evidence of work-hardening, extending 3 mm. below the surface, but the hardness on the actual surface was much higher, rising at one point to 64·8 (648 Brinell). Time-work-hardening tests in the two regions gave the following results :—

Passes of Ball :	0.	2.	4.	6.	8.
Time hardness ...	25·8	33·6	34·0	34·4	33·6
	28·6	35·6	36·2	36·0	—

In this case the maximum hardness on the surface (64·8) was very much higher than the maximum

hardness induced by the pendulum. To account for this, it must be remembered that a locomotive tyre in service is subjected not only to work-hardening by abrasion and shock, but also to the action of sand used in braking, and to very high temperatures generated by friction. It seems safe to infer that the hardness induced by wear in the surface of a locomotive tyre is not less, but generally greater, and occasionally much greater, than the maximum hardness that can be induced by the pendulum. The original hardness of the tyre has no importance in relation to resistance to abrasion, since steel possessing this hardness is not in contact with the rails after the tyre has been in use.

FIG. 5. TOOTH OF WORN GEAR B TESTED FOR HARDNESS. × 10 (REDUCED TO ⅔).

FIG. 8. TIME-WORK HARDENING TEST IMPRESSION IN MILD STEEL. × 100.

A similar investigation was made on a series of worn-out rails, and typical results are given in Fig. 3. The result of the pendulum time-work-hardening test is given below the figure. The rail, Fig. 3, gave the highest maximum induced hardness, 35·5 (355 Brinell). A considerable degree of hardness was induced by abrasion in service, this induced hardness being greatest on the surface and extending some depth into the body of the rail, but in no case was the hardness induced by service equal to the maximum induced by the pendulum. It is evident, however, that the original hardness of the rail can have no importance in relation to resistance to wear, since steel possessing this hardness is not in contact with the wheels of the rolling-stock. Although the hardness induced in the rails investigated was not equal to the maximum of which the steel was capable, it is probable that a different result would be obtained from the end of a rail, as this portion is subjected to severe shock. It is common practice to employ manganese steel for points and crossings, this steel being soft, but possessing an abnormally high work-hardening capacity (see Table II).

B. *Superhardening of Hard Steel Gears and Cams.*— Investigation was made of a number of worn gears and cams which had been discarded from automobiles. The procedure was to make diamond time-hardness tests with the pendulum on the worn and unworn surfaces. In the case of gears, a particular tooth was selected, and the adjacent teeth on either side were ground away so as to expose the selected tooth and allow the pendulum to be balanced on any part of the worn surface. The selected tooth was then cut out by grinding with a thin emery wheel flooded with water. The tooth was mounted in pitch, a section was made by hand-grinding, and this was polished, etched, and tested for hardness at many points with the pendulum and a 1-mm. diamond. The cams were dealt with in a similar manner, worn and unworn surfaces being first tested for hardness, and sections being made through the worn portion. A tooth of a worn gear is shown in Fig. 5, and a chart giving the

results of the hardness tests in Fig. 5A. The diamond time-hardness corresponding to each of the test impressions can be readily seen from the chart, and the results of hardness tests made on the surface are also given, with arrows to indicate the approximate position of the test. Diamond time-work-hardening tests were made on the unworn ends of the teeth of each gear, and the following results are typical :—

Passes of Diamond :　0.　　2.　　4.　　6.
Gear B (Fig. 5) diamond
time-hardness　...　36·2　54·4　57·1　57·0

It was found that all the teeth investigated were very much superhardened by use, the hardness being greatest on the surface, but extending an appreciable distance below the surface. In each case there was clear evidence that the hard steel had been caused to
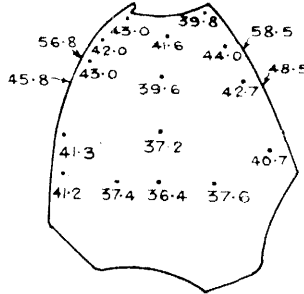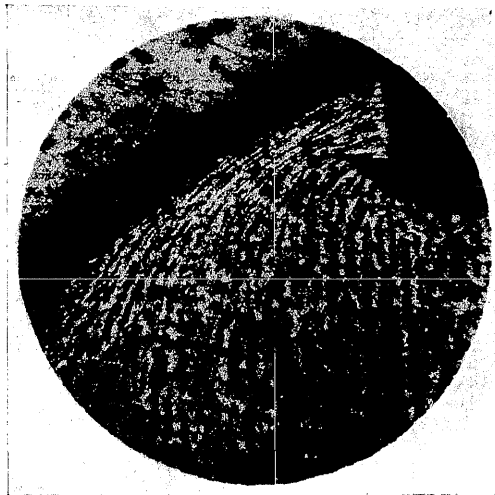

FIG. 5A. DIAMOND TIME-HARDNESS OF GEAR TOOTH B.
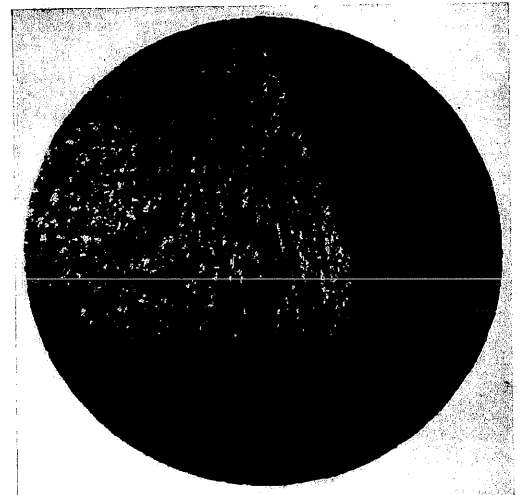

FIG. 9. FLOWED STEEL AT POINT OF HARD GEAR TOOTH B. × 50.

flow by the shock of engaging the gears (all the teeth were from change gears, and had been rounded to facilitate engagement), and this flow is even more clearly seen in Fig. 9, which shows the flowed steel at the point of gear tooth shown in Fig. 5, and in Fig. 10, which shows the pitch point on another gear tooth where the principal shock occurred. The results of this investigation are summarised in Table III :—

TABLE III.—*Diamond Time-Hardness of Three Gear Teeth.*

	Original Hardness.		Induced by Service.		Induced by Pendulum.	
	Time.	Brinell.	Time.	Brinell.	Time.	Brinell.
Gear B	36·3	490	58·5	790	57·1	771
Gear C	35·9	485	48·6	657	51·2	690
Gear D	36·2	489	53·6	723	53·9	729

The average original hardness of each tooth is given, together with the highest hardness reading obtained on the surface, and the maximum induced hardness given by the diamond timework-hardening test. In each case the diamond time-hardness number has been multiplied by 13·5 to give the approximate Brinell hardness. From these figures it appears that :— (a) The original hardness of the three gears was nearly equal. (b) Their capacity for work-hardening was very different. (c) The maximum hardness induced by wear and the maximum hardness induced by the pendulum were in the same order and corresponded

closely. (d) The original hardness gave no indication of the hardness that would be induced by wear. (e) The original hardness of the gear could have no importance in relation to its resistance to wear, since steel possessing the original hardness did not exist in the worn surfaces.

A similar investigation was made with two worn cams from automobiles. Diamond time-hardness tests were made with the pendulum on the worn surfaces of the cams.

TABLE IV.—*Diamond Time and Brinell Hardness of Two Cams.*

	Original Hardness.		Induced by Wear.		Induced by Pendulum.	
	Time.	Brinell.	Time.	Brinell.	Time.	Brinell.
Cam F	60·2	815	86·0	1,160	85·2	1,150
Cam G	54·5	735	75·3	1,020	88·7	1,195

The results of the hardness and work-hardening tests on cams are summarised in Table IV. In cam F the hardness induced on the surface by wear corresponded closely with the maximum hardness induced by the pendulum. Cam G, though originally less hard, had a much higher work-hardening capacity. The worn surface was intensely hard, but had not reached its maximum. Cam G was much less worn than cam F. In this, as in previous cases, it is evident that the original hardness had no importance in relation to wear resistance, since original hardness did not exist in the worn surfaces.

In view of these results, several questions present themselves. Does wear always produce work-hardening ? What conditions are most favourable for its

FIG. 10. FLOWED STEEL AT PITCH LINE OF HARD GEAR TOOTH C. × 50.

production ? How does the chemical composition of the steel affect its work-hardening properties ? It seems probable that work-hardening does not occur in hard or soft metals unless abrasion is sufficiently severe to produce permanent deformation or plastic flow of the surface layer. It is known that manganese steel has an exceptional ability to resist abrasion in railway points and crossings, rock-crushing machinery, &c., in which cases abrasion is so severe as to deform the soft steel and work-harden the surface. But manganese steel gives poor results when used for grinding or crushing soft substances such as cement. It is worn away without deformation of the remaining surface, and therefore without work-hardening.

All the gears and cams in the foregoing investigation had certainly been subjected to shock in addition to frictional wear. Investigation of a worn screw gear A, as used for driving automobile camshafts, showed that none of the worn surfaces were harder than the unworn. A time-work-hardening test was made on this gear with the following result :—

Passes of Ball :　　0.　　2.　　4.　　6.
Diamond time-hardness　49·4　72·4　76·2　76·6

Passes of Ball :　　8.　　10.　　12.　　14.
Diamond time-hardness　77·8　82·0　82·2　81·4

Thus, screw gear A had a high work-hardening capacity ; it was considerably worn, but had not been hardened by wear, which in this case consisted of frictional abrasion between relatively large surfaces of contact. The composition of the various gears and

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cams are given in Table IVa. It will be observed that gears B, C, and D were supposed to be made of the same steel similarly hardened, but the gears were made at very different periods and must have been differently treated, as shown by the work-hardening test and the microstructure. Their original hardnesses were nearly equal.

TABLE IVa.

	Carbon.	Manganese.	Nickel.	Chromium.	Silicon.	Sulphur.	Phosphorus.	
	per cent.	per cent.	per cent.	per cent.	per cent.	per cent.	per cent.	
Screw gear A	0·15	0·35	5·0	0·30	0·30	0·05	0·05	Case hardened.
Gears B, C, and D	0·35	0·50	3·75	1·20	0·20	0·04	0·04	Hardened from 83 deg. C. in oil.
Cam F	0·11	0·70	—	—	0·21	0·06	0·02	Case hardened.
Cam G	0·18	0·75	— —	—	0·10	0·04	0·04	Case hardened.

TABLE V.—Comparison of Superhardening Properties of Alloy Steel and Carbon Steel.

	Alloy Steel.		Carbon Steel.	
	Original.	Maximum.	Original.	Maximum.
Gear A	49·4	82·2	49·6	64·6
Gear C	35·5	51·0	35·5	40·7
Cam F	60·2	85·2	60·6	79·4
Cam G	54·5	88·7	55·4	71·4

In order to ascertain the effect of the composition of steel on its superhardening properties, a specimen of plain carbon steel (1·25 per cent. carbon) was hardened unevenly and spots were selected, the hardness of which corresponded with the original hardness of each of the gears and cams. On the selected spots time-work-hardening tests were made. The original and maximum induced hardness of each spot is given in Table V., together with the original and maximum induced hardness of the corresponding gears and cams.

From this it appears that in every case the hard alloy steel was capable of attaining a higher induced hardness than plain carbon steel of equal or slightly greater hardness. The superhardening of hard steel demands much more extended study than it has yet received, but it is hoped that the present research may serve as a useful introduction to a subject of great practical importance.

THE SOLUTION OF CEMENTITE IN α-IRON AND ITS PRECIPITATION.*

By J. H. WHITELEY, F.I.C.

THE extent to which carbon is soluble in α-iron is a question which has, so far, not been satisfactorily settled. Whilst admittedly it cannot in any case be large, metallurgists are by no means agreed on the exact amount. Recently Sauveur stated that in ordinary steels ferrite contains 0·06 per cent., and Hatfield said that between 0·04 and 0·05 per cent. is present. Both these statements were based on the non-observance of cementite in steels of these carbon contents. In the present paper a number of observations are recorded, which indicate very definitely that, at any rate above 630 deg. C., α-iron does dissolve an appreciable quantity of cementite. It is somewhat surprising that the effect produced by the precipitation of this dissolved carbide at lower temperatures appears hitherto to have been overlooked.

The observation, which first directed the author's attention to the subject, was made while examining a specimen of mild steel which had, for a certain purpose, been twice heated to 680 deg. C. and quenched in water. Minute particles of cementite, readily stained with hot sodium picrate, were seen under a high magnification at the grain boundaries. This effect was quite unexpected because it was completely absent after the first quench, and a considerable amount of work was done before it became clear that solution of cementite in α-iron at 680 deg. C. was the real cause. During the investigation a dozen or more different steels were experimented with, but, as similar results were obtained with all, attention need only be directed to those most frequently used. A description of these is given in Table I.

Fig. 1 shows the structure of an etched specimen of sample B after it had been heated for one hour at 680 deg. C. and quenched in water. On repeating this treatment, the effect shown in Fig. 2 was obtained. It will be seen that the ferrite grain boundaries were clearly outlined by the presence of minute cementite particles. The same area, after staining with sodium picrate, is shown in Fig. 3. Cooling the piece down in the furnace to 680 deg. C. from above A_3, before the first quench, made no difference, provided the subsequent

cooling to room temperature was sufficiently rapid. This was found to be an essential condition ; when the rate was such that the specimen reached approximately 100 deg. C. in less than one minute, these cementite particles were to be observed between the grains, but not when the time was increased to two minutes. Further, the effect was produced equally well, when the specimens were quenched the first time from temperatures somewhat above Ac_1, but for the second treatment it was found necessary to keep below that point. Only very short heatings were then required, a pause of one minute at between 660 deg. C. and 680 deg. C. being sufficient. After a prolonged second heating no increase in the quantity of this cementite could be detected; the particles were larger, but less numerous.

These facts having been established, the problem was to discover the nature of the change during the second heating, which caused the rapid appearance of cementite at the grain boundaries. The solution of carbon in the α-iron seemed the most probable explanation, but no clear picture of what took place could at first be formed. Eventually, an insight into the processes at work was obtained by heating the quenched specimens the second time at progressively lower temperatures, as indicated below, and then making a very careful examination of the ferrite grains.

Between 650 deg. C. and 550 deg. C., it was found that the effect could still be produced in one minute, and, moreover, a distinct increase in the amount of " boundary cementite "* was noticeable at the lower temperatures. When a specimen of sample B was heated for 20 minutes at 450 deg. C., boundary cementite was again found to be present, but to a lesser extent. At this stage it was noticed that a large number of particles too small to be identified were present in the ferrite grains. It was further seen that, at places adjacent to the pearlite areas, these particles were much less numerous, for the ferrite there was almost clear. On heating specimens of steel C at 350 deg. C., a still greater quantity of these fine particles was seen, while boundary cementite was now almost entirely absent. This discovery at once suggested that a cloud precipitation of cementite, dissolved by the α-iron in the first heating at 680 deg. C., had occurred; and that it was the movement of this precipitated cementite out of the grains at higher temperatures, which caused the formation of the boundary cementite. Evidence obtained by further experiments with different steels fully confirmed this conclusion.

Precipitated cementite could be seen in the ferrite of specimens, which had been heated for four hours at 250 deg. C., but no indication of any outward movement at that low temperature could be detected. The minute particles appeared to be very uniformly distributed, and boundary cementite was completely absent. A similar effect was obtained by heating for a short time at 350 deg. C., but after 20 minutes at this temperature, a little boundary cementite appeared. As the temperature was raised further, the time required for the whole of the precipitated cementite to move to the grain boundaries steadily diminished until, when 500 deg. C. was passed, the movement became extremely rapid. A few tests were made in order to determine whether initial precipitation at a low temperature seriously interfered with the rate of the subsequent movement at a higher temperature. Two pieces of the same steel were quenched from 720 deg. C.

TABLE I.

Description.	Combined Carbon	Silicon.	Phosphorus.	Sulphur.	Manganese
	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.
A.—Basic steel of the " Armco " type	0·035	Trace	0·006	0·026	0·02
B.—Acid steel plate heated to 1000 deg. C. and air-cooled	0·18	0·018	0·057	0·065	0·56
C.—Acid steel plate heated to about 1400 deg. C. and cooled very slowly	0·19	0·018	0·06	0·071	0·54

and one was heated for three minutes at 450 deg. C. They were then both heated for one minute at 550 deg. C. and compared. As far as could be judged, the initial precipitation at 450 deg. C. did not cause any appreciable retardation of the migration. In each case the ferrite grains were practically free from visible cementite particles.

The surprising rapidity of the cementite movement to the grain boundaries after precipitation recalled some observations recorded by the author in a paper on martensite.* It was there shown that, on reheating at 600 deg. C., small mild steel specimens, which had been rapidly cooled in hydrogen from 900 deg. C., the carbide particles in the sorbitic grains very quickly found their way to the margins. The author has recently come across a striking instance of the same effect in a quickly-cooled, acid-steel bath sample containing 0·20 per cent. of carbon. A spoonful of metal with a layer of slag on top was withdrawn from the furnace and cooled by immersion in water. When sectioned vertically, the sample was found to have a uniformly sorbitic structure for some distance below the upper surface ; then, for a short distance further in, the retardation of the rate of cooling had been sufficient to allow time for the carbide particles of the sorbite grains to move to the boundaries. Since the time taken in cooling the sample was not more than 30 seconds, it is very evident that the carbide must have moved to the margins after precipitation with great rapidity.

Another instance, from which the same remarkable speed of movement may be inferred, was noted during the present investigation. It was found that if the specimens after the first heating were air-cooled to about 100 deg. C. in one minute or less, boundary cementite was usually produced, and a second heating was not required. With this rate of cooling, the temperature range, in which rapid movement occurred, would be passed in a few seconds, yet this was evidently sufficient for its completion.

In the experiments so far described the temperature of the first heating lay always between 680 deg. C. and 720 deg. C. The next step was to ascertain the lowest temperature at which cementite would dissolve in α-iron in sufficient quantity to produce a visible boundary deposit. Several specimens of different steels were heated for four hours at 600 deg. C., so as to allow ample time for solution and diffusion of the carbide. After quenching, the pieces were heated for two hours at 400 deg. C. In no instance could either boundary cementite or a cloud precipitation be detected. By gradually raising the temperature, distinct evidence of solubility was first observed in sample A after it had been heated at 630 deg. C., but with other steels, such as samples B and C, it was not until a temperature of 650 deg. C. was reached that any boundary cementite appeared. These tests proved conclusively that the solubility range for α-iron extends considerably below the A_1 point and that its range varies somewhat for different steels. The purer the ferrite the greater this range appears to be. Further, it was clearly seen that the solubility increased with the temperature, for the amounts of cementite deposited at the boundaries in the above tests were much less than the quantities previously observed, when higher temperatures were employed.

Carbide dissolved in α-iron diffuses very quickly; and it is for this reason that specimens must be rapidly cooled after the first heating. Otherwise, during cooling, as the solubility diminishes, precipitation will occur on the cementite enclosing the pearlite areas, and few, if any, new crystals will form. The rate of cooling and grain-size are the two factors, which apparently determine the position finally occupied by the precipitated cementite, for, obviously, the greater the distance it must travel to reach a pearlite grain, the more likelihood there is of new centres of growth appearing, especially if the cooling is rapid.

As previously stated, boundary cementite was first seen in specimens, which had been quenched twice from 680 deg. C. The explanation of this can now be given. In the first heating cementite was dissolved in the α-iron, and was retained in solid solution by quenching. During the second heating it was precipitated in the early stages, and then rapidly migrated to the grain boundaries, as the temperature increased towards 600 deg. C. The speed of this movement is such that there would be ample time for the process to be completed within two minutes, the time occupied in reaching 680 deg. C. It might be expected that the minute boundary particles would dissolve more readily in the α-iron on passing 650 deg. C. than the much larger masses of cementite enclosing the pearlite grains. In the present case this effect appeared to be outweighed by the extremely rapid rate, at which the dissolved carbide diffused in the α-iron. Even after a prolonged heating at a temperature just below the Ac_1 point, the boundary cementite showed no tendency to