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OTTAWA August 29, 1940.

REPORT

of the

ORE DRESSING AND METALLURGICAL LABORATORIES.

Investigation No. 889.

Investigational Work on Universal Machine
Gun Carrier Malleable Iron Track Links.

BUREAU OF MINES
DIVISION OF METALLIC MINERALS

ORE DRESSING AND
METALLURGICAL LABORATORIES

CANADA
DEPARTMENT
OF
MINES AND RESOURCES
MINES AND GEOLOGY BRANCH

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Nature of Work:

According to the British War Office specifications, machine gun carrier track links are to be made of whiteheart malleable iron case-hardened by a cyanide heat treatment. The finished links are required to withstand a load of 10,000 pounds when bent between 8-inch centres. They must also have a file-hard surface and a bending angle of at least five degrees on the broken sample.

In the making of the whiteheart malleable iron, a portion of the carbon from the cast-iron is removed by oxidation. However, excessive oxidation during the process of decarburization besides burning the carbon will also tend to build up a heavy scale at the expense of the iron casting. This detrimental effect can be considerably decreased by adjusting the composition of the cast iron, and by using proper methods in the decarburization process. The following report discusses different possible decarburization methods and some particular properties conferred by various heat treatments. This investigation also describes the results obtained on the finished articles, and gives a detailed account of the chemical tests, bend tests, break tests, hardness tests, and microscopic examinations.

Origin of Material:

The iron castings used in this investigation were sent by the International Harvester Co. of Canada, Limited, Hamilton, Ontario.

Macroscopic Examination:

The links cast by the International Harvester Co. of Canada, Limited, appeared to meet with the dimensional requirements of the War Office specifications, except for the bearing holes at each end of the link. These holes were found to be a little oversized. Furthermore, a careful inspection of the castings revealed the presence of several blow holes.

Chemical Analysis:

A sample taken from one of the castings analysed as follows:

Carbon	2.90 per cent
Manganese	0.27 per cent
Silicon	0.59 per cent
Sulphur	0.057 per cent
Phosphorus	0.111 per cent

Decarburization Tests:

The castings were decarburized through the use of (1) a solid oxidising medium; (2) a gaseous oxidising medium.

1. Decarburization through the use of a solid oxidising medium: The method used in Europe to obtain whiteheart malleable castings consists in heating the article at 1600° to 1700°F for several days in a suitably treated packing of iron oxides. Experiments were therefore conducted to determine the conditions under which the oxidation of carbon could take place in a solid packing medium without formation of excessive scaling. European cast-irons are relatively low in silicon and manganese, though high in sulphur. Irons of this composition decarburize more readily, as their carbides are more stable. Higher silicon content also tends to increase scaling, due to this highly oxidisable constituent. (Ingall and Field, Jour. Iron & Steel Inst., 1, 265, 1925)

The different packing media used were composed of hematite or mixtures of hematite and mill scale provided by the International Harvester Co. of Canada, Limited. Bars of cast-iron of the type mentioned were embedded in some packing medium placed in a well luted pot. The following table lists the media used, and the total oxygen present in the various media:

No.	Hematite, per cent	Mill Scale, per cent	Oxygen content, per cent
1	100	-	67.9
2	75	25	69.2
3	60	40	69.8
4	30	70	71.2
5	-	100	72.7

The scale thickness was derived from the actual measurements of the bars before and after heating in the various mixtures for 96 hours at 1670°F. The cooling rate in this, and in all subsequent experiments, was approximately the same and averaged 1°F per minute between 1600°F and 1000°F. At the end of every 96-hour cycle, the cast-iron bars were removed for examination and replaced by new ones of the same original weight.

Decrease in the Total Thickness of Bar

No.	A	B	C
1	Averaging 1/16 inch	.088 inch	.023 inch
2		.081 inch	-
3		-	.012 inch
4		.069 inch	-
5		.054 inch	-

A--Mixtures of fresh oxides.

B--Mixtures of oxides after undergoing 96-hour annealing cycle.

C--Mixtures of oxides after undergoing twice this 96-hour annealing cycle.

Layer samples were taken from No. 1C and 3C and analysed for carbon. The following results were obtained:

	Carbon content, per cent	
	1C	3C
Content of original casting	2.90	2.90
1st layer, 1/32 in. from surface	0.48	0.53
2nd layer, 1/32 in. to 1/16 in. from surface	1.06	1.07
3rd layer, 1/16 in. to 3/32 in. from surface	1.39	1.46
4th layer, 3/32 in. to 1/8 in. from surface	1.80	1.92

A link weighing 3 pounds was embedded in approximately 5 pounds of a mixture of 60 per cent hematite and 40 per cent mill scale. It was kept at 1670°F for 96 hours and cooled at the rate of 1°F per minute down to below the lower critical point. A heavy scale was noticed on the surface of the casting. After sandblasting away this scale, the bearing holes were found to be approximately 0.045 inch larger than before the heating.

The following table shows the variation in the carbon content of this link and of a link treated by the International Harvester Co. of Canada, Limited, in their regular packing material for 100 hours at 1600° to 1700°F:

(Next page)

Layer	Zone from	Carbon content, per cent A	Carbon content, per cent B
1st	0 to 1/32 in.	0.48*	0.51
2nd	1/32 to 1/16 in.	0.71	1.15
3rd	1/16 to 3/32 in.	1.02	1.05
4th	3/32 to 1/8 in.	1.23	1.82
5th	1/8 to 3/16 in.	1.39	2.18
Original content		2.90	2.90

*--Carbon value high at surface due to cyaniding.

A--Link L1 decarburized in a mixture of 60 per cent hematite and 40 per cent mill scale at 1670°F for 96 hours.

B--Link decarburized by the International Harvester Co. of Canada, Limited, for 100 hours at 1600° to 1700°F in their regular packing.

2. <u>Decarburization through the use of a gaseous oxidising medium</u>: Three different methods of decarburization were tried--(1) with a "synthetic" flue gas, (2) with a stream of pure carbon dioxide, (3) with carbon dioxide in a stationary system.

A mixture of nitrogen, carbon dioxide, and oxygen was tried as a decarburizing medium. It had the following composition, averaging that of flue gas, with the exception of its water vapor content and traces of sulphur dioxide:

Oxygen	6 per cent
Carbon dioxide	12 per cent
Nitrogen	82 per cent

The gas mixture was passed over the hot castings contained in a closed vessel which was kept at 1680°F for 96 hours. The rate of flow of the gas entering the reaction vessel was kept constant at 170 c.c. per minute throughout the whole operation. The scale was approximately .03 inch thick. The degree of decarburization is given below.

The decarburization of the same type of iron was also tried, making use of carbon dioxide instead of "synthetic" flue gas; and otherwise using the same experimental conditions (96 hours at 1680°F). The scaling was practically nil and the decarburization was fairly good, as shown by the following figures:

Layer	Zone from	Carbon content, per cent A	Carbon content, per cent B
1st	0 to 1/32 in.	0.80*	0.56
2nd	1/32 to 1/16 in.	0.83	0.71
3rd	1/16 to 3/32 in.	1.09	1.08
4th	3/32 to 1/8 in.	1.71	1.36
5th	1/8 to 3/16 in.	2.21	1.68
Original content		2.90	2.90

*--Carbon values high at surface due to cyaniding.

A--Link L2 treated in "synthetic" flue gas for 96 hours at 1680°F.

B--Link L3 treated in carbon dioxide for 96 hours at 1680°F.

A new decarburizing method was tried, using carbon dioxide in a stationary system. The castings were placed in an air-tight vessel on top of a tray containing hematite ore. No portion of the castings was in actual contact with the ore. At the start, the air in the vessel was replaced by a carbon dioxide atmosphere and the whole system was heated to 1680°F for 96 hours. The decarburization, in such a system, would take place through the carbon dioxide which would be continually regenerated by the action of the hot metallic oxide (after being transformed into carbon monoxide in contact with the iron carbide of the castings). The same experiment was also tried at a higher temperature--1740°F. Upon completion of the treatment, the specimen showed no appreciable amount of scaling. On analysis, the following figures were obtained:

Layer	Zone from	Carbon content, per cent A	 B	 C
1st	0 to 1/32 in.	0.71*	0.69*	0.76*
2nd	1/32 to 1/16 in.	0.86	0.84	0.73
3rd	1/16 to 3/32 in.	1.38	1.51	1.14
4th	3/32 to 1/8 in.	1.90	1.98	1.93
5th	1/8 to 3/16 in.	2.10	2.12	2.06
Original content		2.90	2.90	2.90

*--Carbon values high at surface due to cyaniding.

A--Link L4 treated at 1680°F for 96 hours.

B--Link L6 treated at 1680°F for 96 hours.

C--Link L5 treated at 1740°F for 96 hours.

Cyaniding Treatment:

Prior to cyaniding, the surface of the casting was well sandblasted. A double cyaniding treatment was then given to the decarburized castings. The purpose of this double treatment is to obtain a tough core, together with a hard case. The links were first heated for 40 minutes (total time) to 1750°F in a cyaniding bath of the following composition:

Sodium cyanide*	50 per cent
Sodium carbonate	30 per cent
Sodium chloride	20 per cent

*--Approximately 1.5 per cent of sodium cyanide was added for every hour of heating to keep the proper concentration.

They were then cooled in air at room temperature, reheated to a temperature above the critical range of the high carbon case (about 30 minutes total time), and quenched in a pure mineral oil to prevent any saponification. This oil was kept at room temperature.

The drawing was done at various temperatures ranging from 400°F to 565°F for about 1 hour. No appreciable variation of surface hardness was noticed for these different drawing temperatures.

The first treatment was the same for all the different links treated, i. e., 40 minutes heating to 1750°F in the cyanide bath and cooling slowly in air. The second treatment of each link will be considered separately:

Link L1 - (Decarburized in a 60-40 per cent mixture of hematite and mill scale for 96 hours at 1670°F.) Heated to 1475°F for 30 minutes; quenched in oil; drawn at 535°F for 1 hour.

Link L2 - (Decarburized in a "synthetic" flue gas mixture for 96 hours at 1680°F.) Heated to 1475°F for 30 minutes; quenched in oil; drawn at 400°F for 1 hour.

Link L3 - (Decarburized in a carbon dioxide stream for 96 hours at 1680°F.) Heated to 1475°F for 30 minutes; quenched in oil; drawn at 400°F for 1 hour.

Link L4 - (Decarburized over hematite for 96 hours at 1680°F.) Heated to 1440°F for 25 minutes; quenched in oil; drawn at 565°F for 1½ hours.

Link L5 - (Decarburized over hematite for 96 hours at 1740°F.) Heated to 1500°F for 30 minutes;

quenched in oil; drawn at 535°F for 1 hour.

Link L6 - (Decarburized over hematite for 96 hours at 1680°F.) Heated to 1400°F for 25 minutes; quenched in oil; drawn at 535°F for 1 hour.

Hardness Tests:

Hardness tests were run on the case and the core of the treated link, the Vickers method being used in all cases. For the core, a 30-kilogram load was used. Hardness determinations on the case were made with loads of 10 kilograms, 5 kilograms, and 1 kilogram on the outside surface and, in several instances, on the inner bearing surface of the link. No appreciable difference was observed between the outside and inner bearing surface determinations indicating that the cyaniding, as well as the quenching, was satisfactory in that particular portion of the link.

Hardness (Vickers)

	Case			Core (30-Kg. load)		
	1-Kg. load	5-Kg. load	10-Kg. load	1 mm. from edge	2 mm. from edge	Centre of core
L1	484	477	473	183	206	331
L2	---	644	673	402	391	309
L3	---	516	---	242	285	365
L4	439	423	385	187	214	223
L5	---	526	514	274	451	291
L6	551	469	---	166	199	234
British-made link	481	310	---	155	---	245

Bend Tests:

The links, treated as mentioned above, were bent between 8-inch centres in an Amsler Universal testing machine, the guide portions of the castings being in a vertical position during the test. The bending angle was calculated for different loads by measuring the permanent deformation at these loads. To measure this deformation, the load had to be removed. In re-loading the link there was probably a certain amount of work hardening which would tend to raise the ultimate breaking load slightly. The values observed for each link are given, together with the measured bend on the broken parts of the link. This bend is greater than that calculated at the ultimate breaking load, due to subsequent deformation after this ultimate load is attained. For comparison, typical values obtained in earlier work on a British-made link are also given.

Load in pounds	Bend in degrees						
	L1	L2	L3	L4	L5	L6	British-made link
5,000	--	--	--	--	--	--	0.2
6,000	0.6	0.3	0.4	0.3	0.2	0.8	--
9,000	1.3	0.7	1.3	1.6	--	2.1	1.1
10,000	1.7	1.0(M)	--	2.2	0.4	3.2	1.7
10,500	--	--	2.1(M) (1)	--	--	--	--
11,000	(7.1)*	--	--	--	--	5.1	--
11,500	--	--	--	4.9	--	--	--
11,800	--	--	--	(M)	--	--	--
12,000	3.0	--	--	--	0.7	6.7	4.6
12,500	--	--	--	--	(M)	--	--
12,550	4.9(M)	--	--	--	--	10.2	--
13,500	--	--	--	--	--	--	8.2
13,550	--	--	--	--	--	(M)	--
13,650	--	--	--	--	--	--	(M)
Measured bend on broken parts	8	3	5	9.5	1	12	12

(M)--Maximum load.

*--After reaching maximum load.

(1)--Inspection revealed a large blow hole at point of fracture.

In actual service most links failed in the bearing holes. A test was therefore made at this point on the finished link L6. The bearing was hammered down until it broke; the bend on the broken parts of the bearing was found to be approximately 20°. Figure 9 shows the radius deformation of the bearing after undergoing the hammering, together with a similar bearing before deformation.

Microscopic Examination:

Samples were cut from the decarburized links before and after the cyaniding treatments. Where the case condition was of interest, the samples were mounted in bakelite to prevent rounding of the edges during the polishing.

All these samples were given a metallographic polish and etched with a 2 per cent solution of nitric acid in alcohol.

Photographs of the outer sections of the decarburized links were taken, prior to any cyaniding treatment, to show the general effect of the various decarburizing treatments (magnification x100). Figure 1 gives the structure of the decarburized surface layer of a link treated by the International Harvester Co. of Canada, Limited, in their regular packing material for 100 hours at a temperature of 1600° to 1700°F. The grey material on the left-hand side is pearlite, the iron carbide eutectoid; the white-grained material on the right-hand side is ferrite, the iron constituent; a few temper carbon particles can also be seen. In the same way, Figure 2 (link L1), Figure 4 (link L2), Figure 6 (link L3), and Figure 7 (link L4) illustrate the degree of decarburization taking place in the outer zone of the castings with different treatments.

Link L5 and link L6 had an outer decarburized zone structure similar to link L4, shown in Figure 7.

The centre core structure of link L1 is shown in Figure 3; rare temper carbon particles are scattered in a pearlite and ferrite background. Figure 5 and Figure 8 illustrate a structure known as the bull's-eye pattern, consisting of dark areas of graphite surrounded by white ferrite areas in a groundmass of pearlite.

Figure 10 (link L1), Figure 11 (link L2), Figure 12 (link L3), Figure 13 (link L4), and Figure 15 (link L5) are all photomicrographs at x100 magnification showing the case on five different links after cyaniding. The outer zones shown all have a lighter etching martensitic structure resting on a troosto-sorbitic inner zone. The substrata of these various cases reveal a wide range of structures. The white areas at the left of Figure 10 are ferrite, the darker ones are pearlite. In Figure 12 is shown a sorbitic pearlite substratum. Figure 13 shows this core region immediately after the case as being an easily distinguishable lighter etching ferrite network enclosing grains of pearlite. The centre of the core in link L4 (Figure 14) represents a structure composed of temper carbon particles surrounded by sorbitic pearlite. Figure 11 shows a martensite and troosto-sorbitic substratum; and Figure 15, a martensite and troostite substratum. Figure 16 (magnification x1000) indicates clearly the presence of martensite and troostite in the core of link L5.

Figure 17 and Figure 18 (magnification x100) show the case and core structure of link L6. The substratum of the case is a ferrite network surrounding pearlite grains; a temper carbon particle can be seen in the troosto-sorbitic zone of the case.

Discussion of Results:

Macroscopic Examination - Dimensional requirements are of importance, as a twenty-link assembly must pass the wrap test. The distance between centres at the bearing holes of the International Harvester Co. of Canada, Limited, link appear to be the same as the British link, but the bearing holes in the former link were larger on the three-bearing-hole side. Although there were not sufficient links available for the wrap test, it is considered that the test could not be passed unless these bearing holes were reduced in size.

Chemical Analysis and Decarburization - The fundamentals of the decarburization process should be reviewed briefly before attempting to consider the influence of various components of cast-iron. It should be remarked at first that decarburization is mainly a surface reaction. The carbon from the inner zone, therefore, has to diffuse to the outer zone before being removed by oxidation. It is obvious that this carbon in the solid phase will migrate to the edge only after undergoing dissolution in the austenite.

For a given decarburization temperature, the solid solution of austenite will tend to reach its saturation. At the start it will do so mainly at the expense of the free cementite present, which will go readily into solution. This will proceed at a fair speed at 1650°F to 1700°F. However, when a point is reached where there is no more free cementite present (50 to 80 hours), the carbon-iron equilibrium will be satisfied by dissolving some of the precipitated graphite. The speed at which the carbon is dissolved will, therefore, govern the rate at which it migrates towards the surface where it is removed. In any case, the speed of oxidation should never go far beyond that at which the carbide is brought to the outer zone. If the oxidation overbalances this migration of the carbon, surface oxidation of the iron will take place due to the lack of a suitable protective atmosphere of carbon monoxide and carbon dioxide generated from the burning carbide in contact with the packing medium. This will result in scaling and, at the worst, in iron oxide penetration. For that same reason, as is shown by some work done by Ingall and Field (Jour. of Iron & Steel Inst., No. 1, 1925), rapid heating will also promote peel growth since in the cooler core the cementite has no time to dissolve and diffuse at a rate necessary to counteract the penetrating oxide. It is therefore obvious that, in the production of a successful malleable iron, the predominant controlling factor is the rate of migration of the carbon from the centre to the surface. As was already shown in a previous report, the addition of any element promoting graphitization (such as silicon and phosphorus) will slow down the decarburization, especially at its last stage, and give rise to peeling and iron oxide penetration. Conversely, any element stabilizing the carbides (such as sulphur and manganese) will have exactly the opposite effect.

In the particular case of sulphur and manganese, it should be stressed that, due to the formation of manganese sulphide, "MnS," the addition of manganese up to a certain point will counterbalance the effect of sulphur. Therefore, the total resulting effect will be due to the excess of sulphur or to the excess of manganese present. By "excess sulphur" is meant the total per cent of sulphur less the manganese in per cent divided by the atomic ratio of the two elements, i. e., by 1.72. Similarly, by "excess of manganese" is meant the total manganese in per cent less the sulphur in per cent multiplied by 1.72.

When a sulphur excess is present, there will be formation of a ferrous sulphide which, because of its stabilizing action on the carbides, will speed up the migration of carbon towards the edge and will prevent scaling. In this special case, the success of decarburization, when using a rather violent oxidising medium like hematite ore, will be closely related to the presence of this excess sulphur. Therefore, as one possible alternative, the sulphur content of whiteheart should rise above the manganese in per cent divided by the atomic ratio of these two elements, i. e., by 1.72. The sulphur content nevertheless should not exceed much 0.30 per cent, otherwise it would be difficult to malleabilize the link core. Due to the close connection between sulphur and manganese, the content of this latter should therefore be adjusted so that the necessary excess of sulphur can be present without going beyond this maximum permissible content. Approximately 0.25 per cent manganese is recommended and about 0.25 per cent sulphur, thus ensuring a slight excess of ferrous sulphide to restrain graphitization and to speed up decarburization. In no case should the phosphorus much exceed 0.10 to 0.15 per cent.

On the other hand, a sufficient manganese excess would have an effect equivalent to the excess sulphur; and in the same way would slow down the growth of the oxide layer which, as already mentioned, is the result of a race between the rate of oxidation and the rate of carbon supply by diffusion from the interior. In this case, just as in the case of sulphur, there is a higher limit to the permissible amount of manganese; otherwise, malleabilizing the link core would become difficult, and this higher manganese content would also have a tendency to lower and widen the critical range of the core--thus giving rise to serious difficulties in the case-hardening treatment. This higher limit was not determined. However, it is felt that, if the manganese content is kept at approximately 0.50 to 0.70 per cent, these difficulties would not be experienced; and a suitable excess of manganese can be thus provided, if the sulphur content is kept as low as possible. From the foregoing consideration, it is apparent that the excess of the carbon-stabilizing element in the specimens submitted to decarburization was slight; thus partially explaining the scaling obtained during the process of decarburizing. This manganese excess would be for that type of iron:

0.27 - (0.057 x 1.72) = 0.17 per cent manganese.

A chemical composition varying between definite values should be chosen for the whiteheart. From experimental results obtained on high-silicon-content whiteheart, it should be emphasized that such high silicon content is to be avoided. Preferably, not over 1.0 per cent should be used. However, care must be taken not to use too low a silicon content; otherwise, on cooling, there might be separation of pro-eutectoid cementite at the centre of the casting, with consequent embrittlement.

The ideal condition of decarburization would be attained through the use of a packing medium which would have a preferential oxidising action on the iron carbide, leaving intact the ferrite. Hematite packing is far from fulfilling this ideal condition, and, if the composition of the whiteheart is not carefully adjusted when using it, scaling will result. However, certain other factors can be modified which will reduce in certain proportion the amount of scaling. The addition of mill scale to the hematite packing can be used with some advantage in that respect. Before using the packing mixture, it should go through an annealing cycle a few times to reduce its oxidising properties. Regeneration of the packing medium can be done by adding a small proportion of new hematite ore after each treatment (generally 1 part of new ore to 4 parts of used ore), or by any other appropriate method making use of a suitable activator such as ammonium chloride.

Link L1 was decarburized in a 60-40 per cent hematite and mill scale mixture. The decarburization was found very satisfactory; however, the scaling was heavy. This scaling might alter the dimensions of the castings beyond expectation and therefore cause serious difficulties.

The use of a gaseous oxidising medium has great potentialities in the manufacture of whiteheart malleable. The use of carbon dioxide in a circulatory system, although giving a lesser degree of decarburization, has the decided advantage of producing a small scale due probably to the protective carbon monoxide atmosphere generated (link L3).

The action of a mixture of gas corresponding to approximately the composition of flue gases (with the exception of water vapor and sulphur dioxide) gave a decarburization approximately 1/10 inch deep. This treatment, however, developed an appreciable scale which appears during the last stage of decarburization (after about 50 hours) (link L2).

More satisfactory results, however, were obtained by just heating the castings in a closed vessel over hematite, after replacing the air at the start by carbon dioxide. Very little scale is formed (links L4, L5, and L6).

The temperature of decarburization has a great influence on the rate of decarburization. A convenient temperature range is 1680° to 1750°F during the first stage of decarburization when the cementite is dissolved into the austenite, and slightly lower during the second stage where the migration of carbon to the surface is the controlling factor.

Heat Treatment - Cyaniding is mainly a carburizing treatment. It is therefore evident that any element having some influence on the solubility or the rate of migration of carbon will consequently affect the speed of cyaniding. In fact, although being opposite in effect to decarburization, cyaniding will be favoured in the same way by carbon-stabilizing elements such as sulphur and manganese. In short, the alloy composition which is more suitable for decarburization, within certain limits, will be found very suitable for cyaniding. The elements promoting graphitization, like silicon, will have a tendency to decrease the speed of cyaniding. Direct proof of this fact has been obtained in experiments not reported here.

An intensely hard-case surface is produced by a double cyaniding treatment as described previously. Great care should be taken in cleaning the surface of the casting before cyaniding: an iron oxide skin or iron oxide penetration will make useless any attempt to cyanide it. A high-pressure sand blast can be used for that purpose.

During the higher temperature cyaniding treatment the temper carbon has a tendency to dissolve in the austenite and migrate towards the edge. However, this first treatment is comparatively of a short duration and no great amount of carbon can reach the outer zone. Slow cooling will then produce a soft ductile core.

In order to retain partly the ductility of the core, the case-hardening should be done by quenching from a temperature slightly above the critical range of the case, as any higher temperature promotes carbon solubility in the core. If the core is well decarburized, this critical range of the case can be exceeded by a reasonable margin without altering too much the ductility of the core. However, when the decarburization extends only to a few thirty-seconds of an inch, the margin by which the change point of the case can be exceeded becomes very small. The choice of the hardening temperature in that case becomes a matter of great importance. The critical margin between the core and case-hardening temperatures will also vary according to the type of malleable iron used. If, for instance, the silicon is high, as in true blackheart, the case-hardening treatment will render the core extremely hard and brittle.

It was found that for a high degree of decarburization (link L1), quenching from 1475°F in oil at room temperature gave a satisfactory core and case.

For a decarburized depth of 3/16 inch (link L3) a temperature of 1475°F was found to be the upper limit, the core just passing the bend test when quenched from this temperature. For an average decarburized depth of 3/32 inch to 1/8 inch the range of temperature for quenching was found to be 1400° to 1420°F. Temperatures of 1475°F and 1500°F were found to give definitely too brittle a core. The right quenching temperature for the type of malleable used was found to give a satisfactory core ductility when the decarburization was not much over three thirty-seconds of an inch. The use of a rather low quenching temperature would also have the advantage of producing a finer-grained case.

Drawing - The properties of the links after quenching are improved by reheating to a certain temperature in order to remove strains and toughen the case. During this process, part of the very hard martensite of the case is converted into fine troostite with consequent softening of the case. It is therefore recommended that the drawing be done at a temperature of 300° to 350°F in order to keep the hardness high enough.

Hardness Tests - All the cyanided links investigated were file-hard in accordance with specification requirements, showing that proper conditions were followed to obtain a good case. The small difference observed with a 5-kilogram load and a 1-kilogram load indicates that the cases are reasonably thick.

To obtain a satisfactory bend test, it was noticed that the core hardness should not exceed definite values. The hardness of a typical casting at different points from edge to centre is shown diagrammatically in Figure 19. This casting was submitted to a double cyaniding treatment, the quenching being done in oil from 1400°F (link L6). The particular structure at these different points is also shown, thus giving a complete picture of the physical conditions necessary to obtain a tough product. It should be noticed that a zone, the hardness of which averages 180 (Vickers), is generally present when the bend obtained is good. In tests conducted on about 25 malleable links, all those which did not meet this condition did not show a particularly good bend (not over 7°).

To ascertain that the inner bearing had come in contact with the cyanide, and especially with the oil, during the quenching process, hardness tests were made on small samples cut from the inner part of the bearing; and they gave results similar to those obtained on other portions of the surface.

Bend Tests - Within certain limits, malleability is more desirable than strength, as in actual use the links have to adjust themselves to the required shape without breaking or causing a break in other parts of the machinery. It should therefore be emphasized that the complete bend test giving the permanent deformation under different loads is the main source of information on the actual usefulness of the finished link.

As can be seen by the results observed on different links, the bend for this particular type of whiteheart varies with the amount of decarburization and the heat treatment. A good bend can be obtained on a highly decarburized link even after hardening the case by quenching in oil from 1475°F. However, to produce the same bend on a slightly decarburized link of this type, the quenching temperature should be carefully adjusted to a value near 1420°F.

Microscopic Examination - The ferrite outer zone and the pearlite-ferrite core of the decarburized castings show the degree of decarburization with different packing media. The casting treated in a mixture of hematite and mill scale (Figure 2) and the one treated in a stream of carbon dioxide reveal a much greater decarburized section than the others. The link decarburized in "synthetic" flue gas, as well as those decarburized over hematite (Figure 7), show large areas of pearlite in a ferrite background, including a few temper carbon particles; which indicates that the cementite was dissolved at this stage and that graphitization was well under way.

The two links which failed to pass the bend test have a much harder core, the constituents of which appear in Figure 11, (link L2: martensite and troosto-sorbite) and also in Figure 15 (link L5: martensite and troostite). This core structure indicates that the case-hardening temperature used was high enough to allow resolution of carbon sufficient to result in the formation of a martensite core. At this temperature, the solution of the ferrite and carbide of the pearlite is complete, as can be seen in Figure 16; which gives an enlarged portion at the edge of the core of link L5 (magnification X1000), showing clearly the martensite and troostite structure.

On the other hand, if the case is quenched from a temperature just above that of the critical range of the case, some ferrite remains and forms a soft background to the hard cyanided case, as can be seen in Figure 10 (link L1), in Figure 12 (link L3), in Figure 13 (link L4), and in Figure 17 (link L6).

In Figure 10 and in Figure 12 is shown the predominating ferrite background; in Figure 13 and in Figure 17 this ferrite structure is reduced to a fine ferrite network enclosing coarse grains of pearlite. This ferrite structure will act as a soft medium between the harder fine-grained core and the hard case, and will thus ensure good ductility.

Sections from the two links which failed on the bend test, link L2 and link L5, do not reveal the presence of any ferrite in the case substratum, as should be expected (Figure 11 and Figure 16).

The inner core of the links which passed the bend test shows the presence of temper carbon particles surrounded by a sorbitic pearlite structure (Figure 14 and Figure 18). The links which failed reveal a much harder structure; mainly, of martensite and troostite (Figure 16).

Conclusions:

This work shows that a good decarburization can be obtained by packing the castings in iron oxide which has been previously heated for a long period in contact with iron. It also gives the influence of silicon, manganese, and sulphur on the decarburization rate and on the scaling. It shows that the sulphur and manganese contents should be carefully adjusted to minimize the scaling, especially when embedded in a highly oxidising medium like hematite ore. As sulphur and manganese are closely related, either an excess of sulphur or an excess of manganese can be used in the composition of whiteheart. By "excess of sulphur" is meant the total per cent of sulphur less the manganese in per cent divided by the atomic ratio of these two elements, i. e., by 1.72. Similarly, by "excess of manganese" is meant the total manganese in per cent less the sulphur in per cent multiplied by 1.72.

When an excess of sulphur is used, manganese should be kept low and, conversely, when an excess of manganese is used, sulphur should be kept low. With regard to the particular condition of production of the International Harvester Co. of Canada, Limited, it is felt that a whiteheart containing an excess of manganese could be used with advantage. In all cases, the silicon content should be kept as low as conditions permit.

For hematite-packing decarburization, the views of Ingall and Field on the growth of peeling with rapid heating are sustained.

It was found that part of the properties of blackheart and whiteheart could be combined by using a low-silicon (0.59 per cent), low-sulphur (0.057 per cent) iron in which the manganese was in atomic excess over the sulphur, thus acting as the carbide-stabilizing element. After decarburizing slightly this particular type of cast-iron in order to obtain a decarburized zone only a few thirty-seconds of an inch deep and then submitting to an appropriate case-hardening treatment, a satisfactory track link was obtained. The temperature at which the high carbon case is quenched should be chosen carefully (1400°F to 1425°F) and should never exceed the critical range of the core. For a well decarburized casting, the case can be hardened by heating to a higher temperature than for a partially decarburized one.

Various methods were tried to obtain the low degree of decarburization sufficient for this particular type of iron. To these methods could be added the ordinary annealing treatment under controlled atmosphere; by the use of an atmosphere tending towards the oxidising side, a sufficient depth of decarburization could thus be obtained. The potentialities of these methods are obvious and it is needless to say that the scaling could be reduced to a minimum by properly adjusting the rate of decarburization, using higher oxidising atmosphere at the first stage of the process when the cementite is going into solution, and decreasing it at the second stage when the slow migration of the carbon towards the surface becomes the governing factor.

For a successful case-hardening, the recommended practice should be followed carefully.

ADDENDUM

At the request of Mr. J. A. Rice, Superintendent, International Harvester Co. of Canada, Limited, we are including an explanatory note on the following results obtained by the Hugh F. Davis Laboratory:

> We have completed our tests on the tank link malleable parts and test bars annealed in the gas-fired carburizing furnace at the knife & bar and report as follows:
>
> Analysis of Iron Used:-
>
> | | |
> |---|---|
> | Silicon | .85 |
> | Sulphur | .072 |
> | Manganese | .29 |
> | Phosphorus | .13 |
> | T. Carbon | 2.80 |
>
> (1) Two sets of bars and links were made with the regular iron of the heat as poured of the above analysis.
>
> (2) Two sets of bars and links were made with the regular iron of the heat to which was added enough Manganese to bring it up to 0.50%.
>
> (3) Two sets of bars and links were made with the regular iron of the heat to which was added enough Sulphur to bring it up to 0.200%.
>
> One set of above was packed in iron ore which had been activated by having gone through annealing cycle twice before, this being the 3rd time.
>
> One set of above was packed in our regular packing material as used at the Malleable Foundry.
>
> Cycle:- 86 hours between 1600° - 1750° F.

(Continued next page)

44 hours were at 1600° F and 42 hours at 1750° F.

Pots were well luted and remained so until opened on conclusion of anneal.

All bars were quite free from scale.

Macroscopic examination: all fractures generally white with slight peppery appearance in central portion, which conformed generally to the carbon concentration shown in table (sheet #2).

As yet a microscopic examination has not been made to determine ratio of ferritic to pearlitic portions. This will be done if thought necessary.

The following table comprises the chemicals and physicals with the respective kinds of packing, comparing the British results....

		% Carbon Concentration Below Surface to					Tensile	Elong.%
Kind of Iron	Packing	1/32"	1/16"	3/32"	1/8"	3/16"	P.S.I.	2"
Regular Analysis	Regular	.82	.82	1.26	1.69	2.20	83325	6.25
" "	Iron Ore	.44	.71	.76	1.14	1.86	82934	6.25
Reg. Built to .50 Mn.	Regular	.95	1.22	1.45	1.69	1.80	80196	4.70
" " " " "	Iron Ore	.54	.58	.82	1.16	1.78	88020	6.25
" " " .200 Sul.	Regular	.66	1.22	1.86	2.18	2.29	82478	6.25
" " " " "	Iron Ore	.86	.90	1.72	2.48	2.62	85086	6.25
British		.68	.89	.99	1.10	1.27	-	-

-- ETC. --

(These results were taken from "WHITE HEART MALLEABLE - TEST NO. 58, July 18, 1940.)

These results, besides finding an explanation in our report, bring also a direct confirmation to our observations concerning the relative influence of sulphur and manganese.

If we consider the regular iron decarburization (first two lines beneath the column headings), the atomic excess of manganese over sulphur is equal to:

$$.29 - (.072 \times 1.7) = .16 \text{ per cent manganese.}$$

This excess of carbon-stabilizing element would favor the decarburization to a certain extent.

Now, let us consider the regular iron built to .50 per cent manganese (lines 3 and 4). The decarburization in this case is good, owing to a fair atomic excess of manganese over sulphur equal to:

.50 - (.072 x 1.7) = .37 per cent manganese.

This manganese excess acts as the stabilizing element and speeds up decarburization.

On the other hand, when the regular iron was built to a value of .200 per cent sulphur, the atomic excess of sulphur over manganese is:

.200 - (.29 ÷ 1.7) = 0.03 per cent sulphur.

The addition of sulphur thus slowed down the rate of decarburization because it reduced the amount of carbide stabilizer to only 0.03 per cent. When the sulphur was low, there was an excess of manganese over that required to form "MnS" of 0.16 per cent. The variation in the amount of effective carbide stabilizer present thus explains the experimental results.

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The microscopic specimens were all etched with 2 per cent Nital.

Figure 1

x100

Outer zone of casting decarburized by the International Harvester Co. of Canada, Limited, in their regular packing.

Figure 2

x100

Outer zone of casting decarburized in a 60-40 per cent mixture of hematite and mill scale at 1670°F for 96 hours.

Figure 3

x100

Core of casting decarburized in a 60-40 per cent mixture of hematite and mill scale at 1670°F for 96 hours.

Figure 4

x100

Outer zone of casting decarburized in "synthetic" flue gas at 1680°F for 96 hours.

Figure 5

x100

Core of casting decarburized in "synthetic" flue gas at 1680°F for 96 hours.

Figure 6

x100

Outer zone of casting decarburized in carbon dioxide.

Figure 7

x100

Outer zone of casting decarburized over hematite.

Figure 8

x100

Core of casting decarburized over hematite.

Figure 9

Approximately x$\frac{3}{4}$

Showing radius deformation of bearing after hammering (left hand side).

Figure 10

x100

Case on decarburized and cyanided link L1.

Figure 11

x100

Case on decarburized and cyanided link L2.

Figure 12

x100

Case on decarburized and cyanided link L3.

Figure 13

x100

Case on decarburized and cyanided link L4.

Figure 14

x100

Core of decarburized and cyanided link L4.

Figure 15

x100

Case on decarburized and cyanided link L5.

Figure 16

x1000

Core of decarburized and cyanided link L5.

Figure 17

x100

Case on decarburized and cyanided link L6.

Figure 18

x100

Core of decarburized and cyanided link L6.

Figure 19

x100

Diagram showing hardness and structure at different distances from the edge of a satisfactory malleable iron link.

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