

DECARBURIZATION OF GRAY CAST IRON

FOR WELDING

By Ping-chao Chen

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A thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Master of Science in Metallurgical Engineering.

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October 4th, 1948

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DECARBURIZATION OF GRAY CAST IRON
FOR WELDING

Introduction

Gray cast iron offers greater difficulties to the welding operator than any other common metal he might encounter. The principal difficulty lies in the "self-quenching" effect, the quenching of the fusion zone or heat-affected area near the fusion zone by the rapid conduction of its heat into the adjacent heavier mass of the cooler base metal. Other factors being equal, whether the cast iron is to be gray cast iron or white cast iron depends on whether it cools slowly or quickly from its molten state. During the process of welding, the prepared surface must be fused in order to get a good weld, but it cools off quickly by the self-quenching effect, and its tendency to solidify as white iron is aggravated by the burning out of silicon (9); therefore, in the fusion zone, layers of cementite result, in the form of the white cast iron structure, which contribute to the brittleness of the weld. The pearlitic matrix of the gray iron in the heat-affected zone outside the zone of fusion also absorbed carbon from graphite flakes

during welding, and thus upon cooling, forms a structure corresponding to that of a hyper-eutectoid steel, which is also quite brittle.

Among the other difficulties in welding gray cast iron are: (1) stresses resulting in unequal expansion and contraction; and (2) formation of gas pockets and holes. However, these can be avoided by employing proper technique in welding.

The object of this research was to work out means to overcome the main difficulty described above. The embrittling effect of welding depends not only upon the self-quenching, which is almost unavoidable, but also upon the high carbon content, which makes the quench serious. One method of avoiding it was suggested by Professor Morton C. Smith of the Metallurgical Department of the Colorado School of Mines. In principle, this consists of decarburizing the gray cast iron to a few millimeters in depth, then welding it with a soft steel rod as filler metal. This procedure is intended to eliminate the cementite layer both in the zone of fusion and in the area next to the fusion line of the weld, for the decarburized base metal in contact with the filler metal would be ferritic in nature, or at least low in carbon content.

The subject matter covering the present research will be discussed in the order outlined below: (1) a brief survey of the available methods of welding gray cast iron;

(2) the proposed method and its related theories of decarburization of cast iron; (3) experiments conducted on the decarburization of gray cast iron; (4) welding of the decarburized samples; and (5) examination of the welded samples.

Welding of Gray Cast Iron

Many methods have been tried in welding gray iron castings, but they have largely been limited to repair and salvage operations only. Because of the difficulties encountered, as discussed in the introduction, the general precautions which must be taken to minimize the unsatisfactory effects of welding are: (1) the surface on which metal is to be deposited must be heated sufficiently to obtain a good bond between the weld and the base metal; (2) the area adjacent to the weld must be heated sufficiently to minimize hardening in the weld zone; (3) other parts of the casting must be heated in such a manner that excessive stresses will not be caused by the welding operation; and (4) the finished weld must be cooled as slowly as possible.

The available methods for welding gray iron casting are:

- (1) Metallic arc welding
- (2) Oxyacetylene welding
- (3) Carbon arc welding
- (4) Bronze welding
- (5) Thermit welding
- (6) Burning

Metallic Arc Welding

For metallic arc welding, either ferrous electrodes or non-ferrous electrodes may be used. The electrodes are made positive, the work negative.

The preparation for making the weld, for instance a repair, consists of chipping away any undesired metal and preparing a groove for metal deposition. For castings up to about $1\frac{1}{2}$ inches in thickness, a V-groove may be used. The weld is then made by the usual arc-welding procedures.

As might be expected, all of the above electrodes produce high hardness and brittleness in the heat-affected zones when the base metal has not been preheated. The hardnesses are somewhat higher for the ferrous than for the non-ferrous types of electrodes, but the difference is not great. Preheating helps somewhat in preventing the appearance of excessive hardness in the heat-affected zone, but cannot completely eliminate it.

Oxyacetylene Welding

Oxyacetylene welding, or gas welding, as it is frequently called, is done with the oxyacetylene torch adjusted to a neutral or slightly reducing flame.

The preparation for making the weld is similar to that for metallic arc welding. The gray iron casting is preferably preheated to low red heat. Cast iron filler rods having about 3.5 percent carbon and 3.0 percent silicon are

suitable, and a special flux is used to remove the oxides. After the welding is completed, the whole casting should be covered so as to cool slowly.

Although preheating and slow cooling are used, the resulting welds cannot be satisfactorily free from the increment of hardness in the heat-affected area.

Carbon Arc Welding

Although carbon arc welding is an arc welding process, it resembles oxyacetylene welding, since the same type of filler rod and flux are used. It differs from the gas welding process in that an arc between carbon or graphite electrodes and the work is used to furnish the heat necessary for making the weld. The same precautions described above must be taken; the casting before welding should be preheated to low red heat, and the whole casting after welding should be covered so as to cool slowly.

Bronze Welding

Bronze welding, or brazing, is very similar to gas welding except that a brass filler rod containing about 60 percent copper and 40 percent zinc is used in place of the cast iron filler rod. Brazing with the electric arc process is also practiced.

When gray iron castings are bronze welded, comparatively little preheating is necessary. It is recommended that two types of flux be used, a "tinning" flux for coat-

ing the surface of the cast iron and a welding flux for the actual brazing operation. These fluxes are commercially available.

A grooved surface should be prepared by chipping rather than by grinding, because grinding tends to coat the cast iron with graphite. Cleaning with a wire brush is helpful, and excess graphite may also be burnt off with an oxyacetylene torch adjusted to an oxidizing flame.

Some of the tinning flux is sprinkled into the groove, and a small area at the point where the weld is to be started is heated to the melting temperature of the brass filler rod, which is about 1650°F. The behavior of the brass on the cast iron indicates when the proper temperature has been reached. If the cast iron is too cold, the brass does not spread out or "tin" the surface, and if it is too hot, the brass collects in little balls on the surface of the cast iron. Bronze welding is done at a temperature several hundred degrees below the melting point of cast iron; this lower temperature is an advantage of this method over other methods since it reduces the embrittling effect of the self-quench.

After the groove is "tinned," the weld is built up in layers until complete, and then the casting is covered and allowed to cool slowly.

Thermit Welding

Thermit welding for gray iron is similar to that for

steel except that cast-iron Thermit mixture is used for gray iron. The process is used for making repairs on many types of structures but is not suitable for welding cracks which extend only partially through a section or for welding long cracks in thin sections.

In preparation for Thermit welding, the ends of the broken member are machined or otherwise cut so as to form a parallel-sided gap at the section which is to be welded. Next, the broken pieces are set up in alignment with proper allowance for shrinkage, and a wax pattern is made to conform to the desired shape of the finished weld. A mold box of suitable size is then set in place around the broken member and filled with molding material with the various gate and riser patterns in their proper positions.

When the mold has been completed, the ends of the casting next to the gap are preheated to a red heat with a kerosene-air or other burner through the gates provided for that purpose. When the preheating, which melts out the wax pattern, is completed, the preheating gates are plugged, and the Thermit mixture in the crucible is ignited. As soon as the reaction is completed, the crucible is tapped, and the metal flows into the space formed by the wax pattern. Because the superheat in the Thermit metal is sufficient to melt some of the iron adjacent to the gap, a bond is thus insured between the added metal and the original casting.

Burning

Although "Burning" is not generally classified as a welding process, it is one of the accepted methods of repairing gray iron castings. Basically, it is quite similar to Thermit welding except that the molten metal for making the "burn" is obtained from a cupola. It is almost exclusively used for repairing heavy castings.

The casting is prepared by chipping or some other means. A dam of loam sand is built around the area so as to form a flow-off for the excess metal. The area of casting around the repair area is preheated to a temperature of 400° to 500°F. by charcoal fire or other convenient means.

Molten iron of suitable composition is taken from a cupola and poured onto the weld area or crack in such a manner as to heat the entire area to be repaired. The pouring is done slowly and continued for one or two minutes after the mold is full, the excess metal being allowed to run out through the flow-off in the dam. Pouring is then interrupted for a short time, perhaps a minute, to allow the heat to soak into the casting and is then resumed for a short time. This alternate pouring and waiting is continued until the area to be repaired is heated above the melting point to insure a proper bonding between the added metal and the original casting. The metal used for pouring should be at a temperature of about 2800°F., and the pouring should not be done after the temperature drops to 2500°F; otherwise an excess of molten metal is required to heat the casting to a

fusion temperature. After the pouring is completed, the casting is covered so as to cool slowly.

All of the above methods share the disadvantage that preheating of parts to be welded is necessary, and none of these methods can consistently produce sound welds in gray iron even when preheating is used.

The Proposed Method and Its Related Theories
of the Decarburization of Cast Iron

The proposed method in this experiment, as mentioned above, consists of two main steps: (1) decarburization of the gray iron casting to a few millimeters in depth on the surfaces to be welded; and (2) welding of the decarburized surfaces with soft, low carbon steel rod as filler metal. This procedure, it was felt, would avoid the undesirable embrittling effect of the welding operation without the necessity of preheating, since carbon--and therefore iron carbide--would be low in the zone of fusion and absent from the heat-affected region.

The process for decarburizing the gray cast iron is quite similar to that for the production of white heart malleable cast iron, except that here the process begins with gray cast iron, whereas the raw material for the latter is white cast iron. Unfortunately, white heart malleable cast iron is a European product, and very little information is available on its production in American publications. For this reason, the major part of the research was devoted to the study of methods for decarburizing the gray iron samples.

W. H. Hatfield's "Cast Iron in the Light of Recent Researches," 1928, and D. H. Ingall and H. Field's "Peeling in White Heart Malleable," 1925, throw much light on the theoretical aspects of decarburization in cast iron. The following paragraphs are abstracted from their articles.

Diversity of Theories Concerning the
Decarburization of Cast Iron

At the beginning of this century, several European authorities advanced different theories concerning the chemical physics of decarburization of white cast iron. They are summarized below:

(a) Ledebur's Theory.--Ledebur (5) explained the process of decarburization somewhat as follows:

"The decarburization is not only confined to the surface of the glowing piece of iron, but also penetrates to the innermost parts. As long as heating is carried on sufficiently and the temperature is high enough, a circulation of carbon takes place. When the amount of carbon diminishes on the surface of the piece of iron, the carbon flows from the inside, so that an equalization takes place."

He further explained "that one could get a conception of the process by imagining that the carbon is given off from molecule to molecule as soon as one molecule becomes poorer in carbon than another."

(b) Wust's Theory.--Wust (5) said that Ledebur's idea of equalization of carbon as here represented can only take

place where carbon is in solution, while the carbon, separated out as free carbon, can in no wise travel from molecule to molecule in the solid iron.

He postulated that the production of malleable cast iron takes place in two distinct stages: (1) Annealing carbon is produced according to the formula; cementite is equal to ferrite plus annealing carbon; (2) the annealing carbon thus produced is converted into gas and then the tempering begins. Hatfield defined the term "annealing carbon" as the apparently amorphous, finely divided carbon, having some graphitic properties, which separates from white cast iron during prolonged annealing and "tempering" as the act of partially or wholly undoing what has previously been done by hardening.

"Since," Wust (5) said, "motion of free carbon cannot take place in the solid iron and equalization of this free carbon, molecule to molecule, is impossible to conceive of, it must be conclusively accepted that the former conception of the process during tempering is untenable. The conversion of annealing carbon into gas would only take place where it has separated out. Thus it takes place not only at the points of contact between the iron ore and the heated iron, but it must distribute itself over the entire cross section of the piece. The carbon does not move toward the oxidizing agent, beginning its activity at the surface, gradually penetrates, and in this manner reaches the annealing carbon which has not yet been oxidized. Accordingly,

the oxidizing agent can only be a gas giving off oxygen, and the oxide of iron used to carry on the process of elimination only thus indirectly effects the conversion of the carbon into gas."

In support of his theory, Wust and his pupil, Schulte-Kemp, carried out an experiment in which the carbon conditions (total carbon and annealing carbon) in the sample, oxygen lost in the iron oxide, and the gaseous products were under examination.

From their experiment, Wust concluded (5) that:

(1) The process of elimination is caused by oxygen which forms carbon-dioxide with the annealing carbon produced during that treatment.

(2) The carbon-dioxide penetrates into the growing iron and forms carbon-monoxide with the annealing carbon.

(3) The carbon-dioxide is again generated when the carbon-monoxide reduces the iron ore into iron-protoxide and metallic iron.

(4) If there is a lack of oxygen in the ore, the regeneration of carbon-dioxide does not occur, and the carbon-monoxide content of the gas mixture can increase to such an extent that, through the decomposition of the carbon-monoxide, the piece is recarburized.

In brief, from Wust's point of view, carbon must be precipitated as annealing carbon before it can be eliminated; and the carbon does not move toward the oxidizing agent but vice versa.

(c) Hatfield's Theory.--Hatfield (5) agrees with Wust that carbon can only diffuse when in solution; but he takes exception to Wust's theory on two grounds:

(1) Carbon can be and is eliminated without its being first precipitated in the free state.

(2) At the temperature of 960°C (1760°F), used by Wust, much of the temper carbon would recombine with the iron.

With regard to the first point, he gave the example that the billet or ingot becomes decarburized on exposure to the furnace gases while free carbon in steel is unheard of. He gave the equations for the elimination of carbon from carbide as follows:



With regard to the second point, he described how he had obtained a material of glass-scratching hardness by quenching a sample of American blackheart malleable cast iron.

He also conducted an experiment in which microscopic examinations of different samples were made. He came to the conclusion summarized below (5):

"At the temperature of 750°C (1382°F), the oxidation

of carbon has been commenced; and since there is no evidence of free carbon's being present at this stage, the carbide itself must have been attacked. The activity of this reaction increased with the temperature, until a temperature is reached at which the precipitation of annealing carbon takes place until equilibrium for the particular temperature and composition is attained. The later stages simply consist of further elimination of carbon from the outer portion, to which carbon is replaced by diffusion of carbon as carbide from the inside of the piece, the latter being also replaced by the precipitated annealing carbon being taken back into solution, and thus preserving the equilibrium for the temperature."

Effect of Silicon Content on Decarburization

Rugan and Carpenter (5) made an investigation of the effect of silicon content on decarburization. A number of cast-iron bars of varying silicon content were heated in a muffle at 900°C (1652°F) for decarburization treatment for a total period of 100 hours. The results are tabulated as follows:

Alloy	% Si	% C in Original Alloy	% C after Treatment	% Loss
N	1.07	3.98	2.45	38.4
O	1.79	3.98	2.40	39.7
P	2.96	3.97	2.60	31.4
Q	4.20	3.76	2.77	26.3
R	4.83	3.79	3.25	14.3
S	6.14	3.38	3.40	nil

The authors said, "The loss is greatest in N and O, which is only to be expected, as these contain the greatest amount of combined graphite. It diminishes with rising silicon, until in S it is nil." (5)

Behavior of Iron Oxide upon Heating

Bergen (5) performed an experiment concerning the liberation of oxygen from iron oxide upon heating. Bergen's results show that the evolution of oxygen from the oxide commences at 600°C (1112°F) with 6 percent loss of oxygen present in the oxide, and follows a straight line function up to 10 percent loss when the temperature reaches 1000°C (1832°F). After that temperature the increase in percentage of loss of oxygen slows down.

Scaling or "Peeling" of Malleable Castings

It is not uncommon in a foundry to find malleable castings on whose surface, after annealing, a well defined skin is found. On fracture, the skin is frequently found to separate mechanically from the body of the casting. The subject has been carefully investigated by Ingall and Field (10). They consider the formation of the "peel" to be the result of oxidation and to be peculiarly likely if the temperature much exceeds 900°C (1652°F). They point out that the growth of oxide layer would depend upon the result of a race between (1) the rate of oxidation and (2) the rate of carbon supply by diffusion from the interior.

They summarized their results as follows:

(1) Metals containing 0.2 to 0.4 percent sulphur will be likely to peel; and the higher the silicon content, the greater the probability.

(2) A temperature of about 950°C (1742°F) is most conducive to peeling. Higher and lower temperatures, though they do not necessarily prevent the formation of peel, retard its growth. With lower temperatures there is, of course, the risk of the material's not being completely malleabilized, and with higher temperature, the possibility of burnt metal.

(3) "Peel" has been found to consist of a layer or layers of ferrite containing free oxide globules as inclusions. When this layer is once formed, it will continue to grow with time, according to temperature conditions.

(4) The work outlined above has not given any definite proof of the mechanism causing the development of peeling.

In connection with the present research, the conclusions noted above may be summarized as follows:

A. The proposed method of welding gray iron in this research consists of first decarburizing the gray iron, and then welding the decarburized sample with soft steel rod. The major part of the research time was devoted to the study of decarburizing gray iron.

B. Because of the possible similarity between the decarburization of white cast iron and of gray cast iron, a survey of the literature concerning the decarburization of white cast iron was made.

(1) European authorities have advanced different theories concerning the mechanism of decarburization. Ledebur said that carbon flows from the inside toward the surface and is given off from molecule to molecule. Wust explained that carbon must be precipitated before being oxidized; the precipitated free carbon cannot travel from inside; instead, the oxidizing gas penetrates from the skin towards the center. Hatfield insisted that carbon can be and is eliminated from the combined form of iron carbide without being precipitated as free carbon. Hatfield is probably right, since he did his experiments at a later date and with more accuracy than the former two authorities. This gives a hint that, for the present problem of decarburizing the gray iron, graphite must first be converted into solid solution or cementite before it is oxidized, especially for the deeper region of the specimen.

(2) Silicon content has a direct effect on decarburization. The loss of carbon after treatment decreases with increase of silicon content in the sample treated.

(3) The oxidizing agent--iron oxide--begins to give off oxygen at the temperature of 1112° F, and its decomposition follows a straight line function of temperature up to 1832° F, then slows down.

(4) Scaling or "peeling" is accelerated by a temperature of about 1740° F, and a composition of 0.2 to

0.4 percent sulphur and a high silicon content in the iron.

From the above summary, it might be inferred that the gray iron when subjected to decarburization treatment would decarburize to a lesser depth and form a thicker scale than the white iron would, because of the former's comparatively higher silicon content. More heat and longer time would be required to get the graphite into solution or combined form before it could be oxidized. It can also be seen that a higher temperature favors the speed of reaction in both the white iron to be decarburized and the iron oxide that liberates oxygen. But, unfortunately, the higher temperature also accelerates the scale formation, which is undesirable. Therefore, it remained for this research to try to find the best conditions for the decarburization of gray iron.

Experiments on Decarburization of Gray Cast Iron

Temperature of Treatment

For white heart malleablizing process, Camp and Francis (4) recommend a temperature range from 1530° to 1650°F., it being understood that the process starts with white cast iron. As for gray cast iron, longer time and more heat would be required to take the graphite into solution before it is oxidized. Use of higher temperature, however, is limited by the formation of scale; as has been pointed out by Ingall and Field (10), the peeling would speed up if the temperature should exceed 900°C (1652°F). This statement gives a rough idea of what the proper temperature should be. However, because gray iron is different from white iron, it was necessary to try various temperatures for decarburization in this research.

Apparatus and Material Used

The furnace used for this experiment was a 3-inch-diameter by 4-inch-deep Multiple Unit electric resistance furnace. The temperature of the furnace was controlled by a rheostat and indicated by a Brown Electric Pyrometer, through a chromelalumel thermocouple. The furnace used

was just big enough to accomodate two 1 7/8-inch-diameter porcelain crucibles in which the samples were packed with iron oxide for treatment.

Samples used throughout the experiments were common gray iron, except for Experiment No. 1, in which the specimen was Meehanite. The size of the gray iron sample throughout these experiments was 1 1/4 inches in diameter and about 5/8 inch in thickness. They were packed in a 1 7/8-inch-diameter porcelain crucibles with "red iron oxide."

The temperature of the furnace was not quite uniform, the bottom part being hotter than the top. The recorded temperature readings for these experiments, however, were made in the upper (cooler) part of the furnace.

Experiments Conducted

Following are descriptions of the ten experiments performed:

Experiment No. 1.--The sample was Meehanite. The annealing temperature was fairly constant at 1580° F, and the period was 4 hours and 45 minutes. The depth of decarburization was 0.3 millimeters.

Experiment No. 2.--This sample and samples for the rest of the experiments were common gray cast iron. The temperature was 1560° F, and the period of treatment was 4 hours and 30 minutes. The thickness of decarburization was 0.55 millimeters.

Experiment No. 3.--The annealing temperature was adjusted to 1600° F, but went up to 1720° F, when the sample was left for treatment overnight. The sample was found highly oxidized and heavily scaled. The period was 20 hours. The thickness of decarburization was 0.55 millimeters.

Experiment No. 4.--For this experiment the temperature was adjusted to 1600° F. The annealing temperature was 6 hours and 15 minutes. The thickness of decarburization was found to be 0.5 millimeters. The limit of decarburized zone was sharp and regular, and the scaling condition was not serious.

Experiment No. 5.--The temperature was adjusted to about 1530° F, and the annealing process was continued on the above sample for a period of 20 hours. The thickness of decarburization was found to be 0.85 millimeters.

Experiment No. 6.--For this experiment, the temperature was originally adjusted to 1400° F, but fell off to 1320° F overnight. Very little scale was formed at the surface during this lower temperature treatment. Decarburization still took place; its depth was found to be 0.45 millimeters.

Experiment No. 7.--The temperature for this experiment averaged 1470° F, and the total time for annealing was 18 hours. The depth of decarburization measured 0.8 millimeters. Scale formed was only about 2 millimeters in thickness.

Experiment No. 8.--For this experiment, fire clay was employed to keep the sample out of contact with the atmosphere, to determine whether there would be any improvement in the scaling condition. The sample was packed in iron oxide in a porcelain crucible, and a cover one size bigger than the crucible was used to furnish an annular space between the top of the crucible and the lip of the cover, into which the kneaded clay was rammed in order to make the crucible airtight. Then the clay was air dried to avoid any cracks caused by sudden intense heat.

The temperature was fairly constant at 1600° F, and the period of treatment was 17 hours. The scaling condition was somewhat improved, but not to a pronounced degree. The decarburization zone was found to shade off into pearlite. The clear depth of the ferrite area averaged 0.95 millimeters.

As the micro-structure of this sample is traced from the skin towards the center, ferrite gradually gives way to pearlite almost free of graphite from the gray iron; further downwards, dots of graphite "vestige" are found on the pearlite matrix; and finally there appears a sharp demarcation line of unaltered gray iron structure as shown in Plate 1, which is an unetched micro-photo in that part of the sample. The "steel" zone from the outer edge of the sample to the unaltered gray iron boundary in this experiment measured 2.1 millimeters.

Plate 1.



100X

Unetched.

The dark spots in the upper part of Plate 1 are the graphite "vestige," the remaining graphite which was not completely eliminated; the dark area in the lower part shows the unaltered gray iron graphite flakes; and the white background of the whole photo is the unetched pearlitic matrix.

Experiment No. 9.--This sample was clay sealed as was done in Experiment No. 8. It was heated up to 1600° F, but for a longer period--45 hours. The thickness of decarburization was 1.4 millimeters and the "steel" zone measured 3.3 millimeters in depth.

Experiment No. 10.--This sample received the same treatment as those of Experiments Nos. 8 and 9, but for a longer period--66 hours. The thickness of decarburization measured 1.6 millimeters and the "steel" zone, 3.5 millimeters. A photomicrographic cross-section of the decarburized sample is shown in Plate 2. The top part of the photo shows the skin of the sample; white areas are ferrite and dark areas, pearlite; and the round, dark spots near the skin are gas holes.

All the records of observation in the above experiments were made from specimens contained in the upper crucible, which was near the top of the furnace. In every case, the sample in the lower crucible reached a higher temperature and consequently showed more scaling and a deeper "steel" zone.

Plate 2.



100X

Picral etched

Curves Plotted from the Experiments

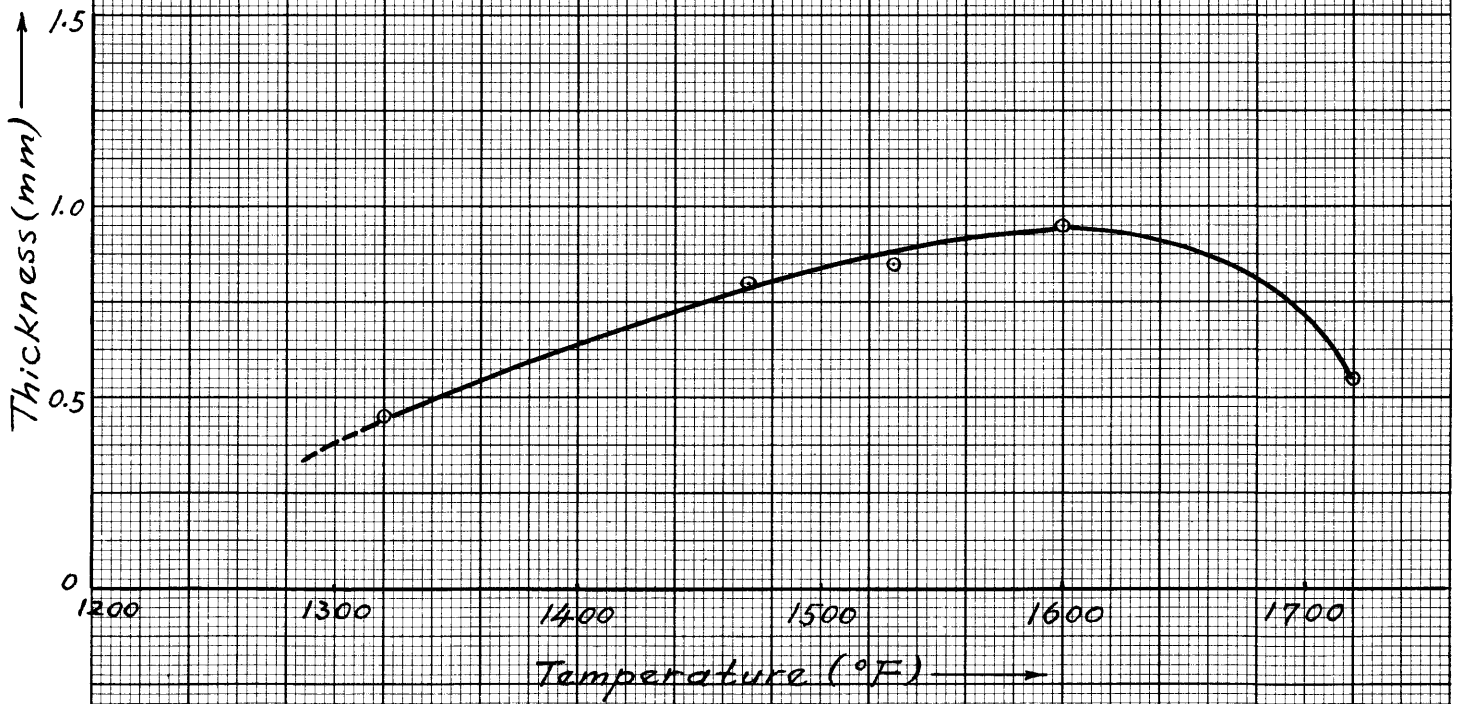
From Experiments No. 3, 5, 6, 7, and 8, Graph No. 1 was plotted. The thickness of decarburization (millimeters) is plotted against the annealing temperature ($^{\circ}\text{F}$). The time of treatment for these samples varies little, the extremes being 20 hours in Experiment No. 5, and 17 hours for Experiment No. 8. The curve thus obtained could serve fairly well to indicate the relation between the depth of decarburization and the temperature employed for treatment. As is shown by the curve, higher temperature increases the rate of decarburization up to about 1600°F . Still higher temperature, for example 1720°F , as used in Experiment No. 3, results in less depth of decarburization and heavy scaling. From this information, 1600°F seems to be the optimum temperature.

From Experiments No. 4, 8, 9, and 10, Graph No. 2 was plotted. All of these samples were treated at a temperature of 1600°F . Depth of complete decarburization, Curve "A" and the thickness of "steel" zone, Curve "B," (millimeters) were plotted against the time (hours) of annealing treatment. From the graph, the microstructure changes resulting from the treatment of gray iron can be visualized. Curve "A" represents the thickness of the decarburized zone, varying from all ferritic structure of the skin down to the margin of entirely pearlite, covering the whole range of hypo-eutectoid steel; the vertical distance between Curve

"A" and Curve "B" represents the thickness of pearlitic structure, corresponding to the eutectoid steel structure; and the thickness above Curve "B" represents the unaltered gray iron structure of the sample.

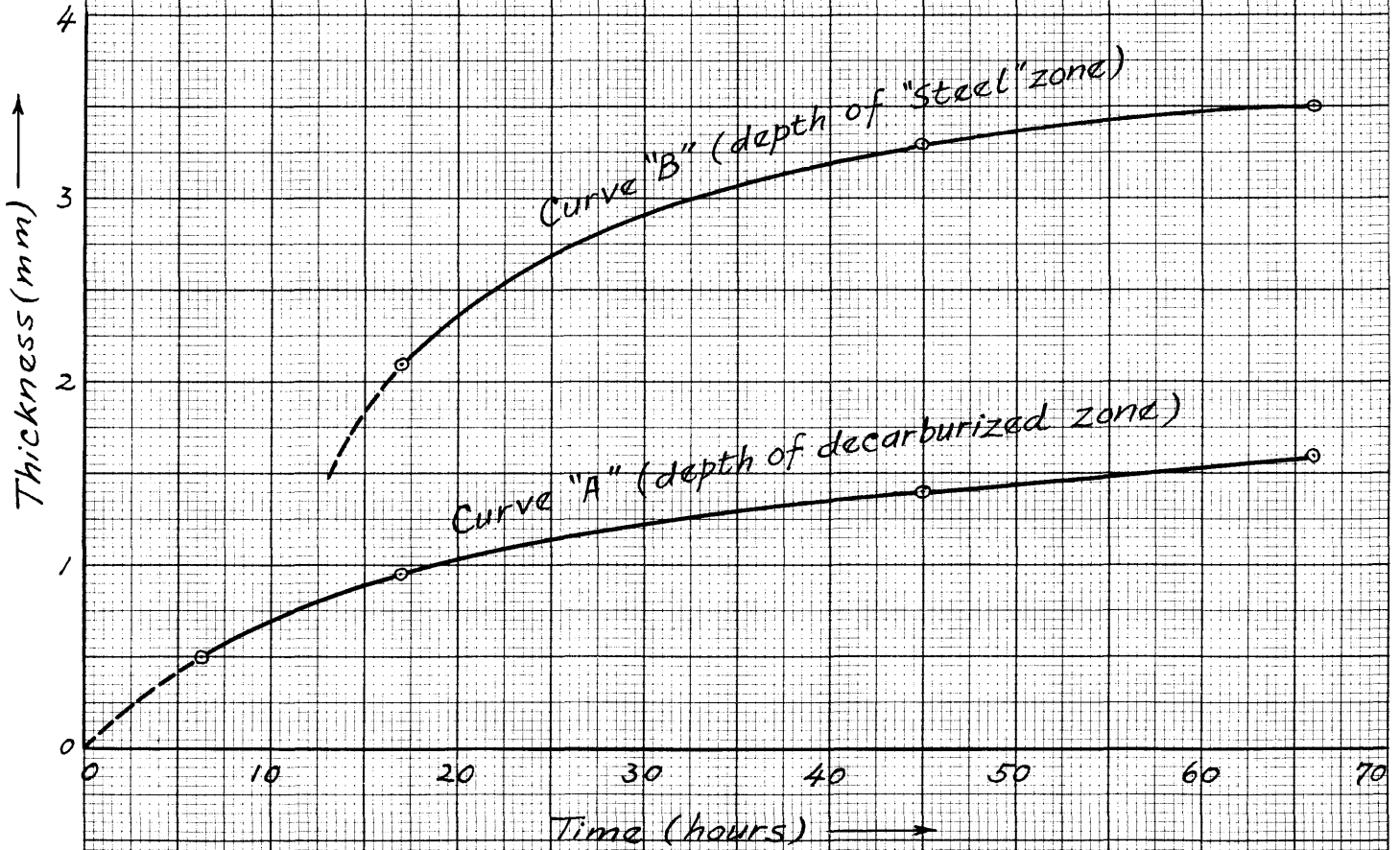
From the above experiments, it may be concluded that when gray iron is decarburized by annealing in iron oxide, the resulting microstructure will be, tracing from the skin towards the center, hypo-eutectoid steel, eutectoid steel with a few graphite "vestiges," and, finally, unaltered gray iron. The depth of the transformed layer depends on the temperature and time of treatment. A temperature of 1600° F is the optimum one for decarburization, and the depth of decarburized layer increases with the time at this temperature. Scaling increases with the increase of both temperature and time.

Graph No. 1

Depth of Decarburization against temperature

Graph No. 2

Depth of Decarburized zone and "Steel" zone
against Time



Welding of the Decarburized Samples

Treated samples from Experiments No. 9 and 10 were used for the gas welding experiments. The samples were first cleaned of the adhering scale by grinding the abutting surfaces, which had been prepared by the decarburization treatment. Welding was done with a Prest-O-Weld oxyacetylene welder, using W-110, W-111 tip No. 5 blowpipe and a pressure of 6 pounds per square inch for both oxygen and acetylene. The cleaned abutting surfaces of the samples were set about 1/8 inches apart. A 1/8-inch-diameter, copper coated, dead soft steel rod was used as filler metal.

A pair of untreated gray cast iron specimens of the same size were prepared and welded in the same manner. This was done to permit comparison of the results obtained from decarburized and untreated gray cast iron, and to cancel out the "size factor" of the "self-quenching" effect--for the greater the mass of the unheated base metal, the more serious the "self-quenching" effect.

Both the treated and untreated samples were welded with neither preheating nor controlled cooling after welding.

Examination of the Welded Samples

Photomicrographs

The welded samples from both the untreated and treated gray iron were sections, ground, polished, and etched with picral for photomicrography. They were all magnified 100 diameters.

Untreated Sample.--The photomicrograph of the zone of fusion of the untreated gray cast iron is shown in Plate 3. The white areas are cementite and represent the white cast iron structure.

Treated Sample.--A series of photomicrographs tracing the structure from the filler metal towards the base metal shows no white cast iron structure formed in the fusion zone as the untreated sample does. The series is shown in Plate 4, 5, 6, and 7.

Plate 4 shows the major part of the filler metal. The white areas are the ferrite, and the dark areas are pearlite. The upper part of the photo shows the dendritic microstructure of the filler metal, which is dead soft steel, and the lower part, that of the skin of the decarburized gray iron.

Plate 3.



100X

Picral etched.

Plate 4.



100X

Picral etched.

Plate 5 shows the metal farther away from the filler metal. The white areas are ferrite, and the dark areas are pearlite.

Plate 6 overlaps Plate 5, showing that the ferrite (white areas) decreases as pearlite (dark areas) increases; pure pearlite appears near the bottom of the picture.

Plate 7 shows the edge of the heat-affected zone. This photomicrograph is taken just next to the position of Plate 6 and is almost on the boundary of the unaltered gray iron region. The microstructure corresponds to that of hyper-eutectoid steel with pearlitic matrix and cementite grain boundary network. The black dots are graphite "vestiges."

Rockwell Hardness Test

Rockwell hardness tests were made on the untreated and treated gray iron samples before welding; and also on the fusion zone and the heat-affected zone of the welded samples for untreated and treated samples respectively.

Rockwell scale A (60-kilogram load, 120° Brale penetrator) was used for hardness tests throughout.

Untreated Gray Iron Sample

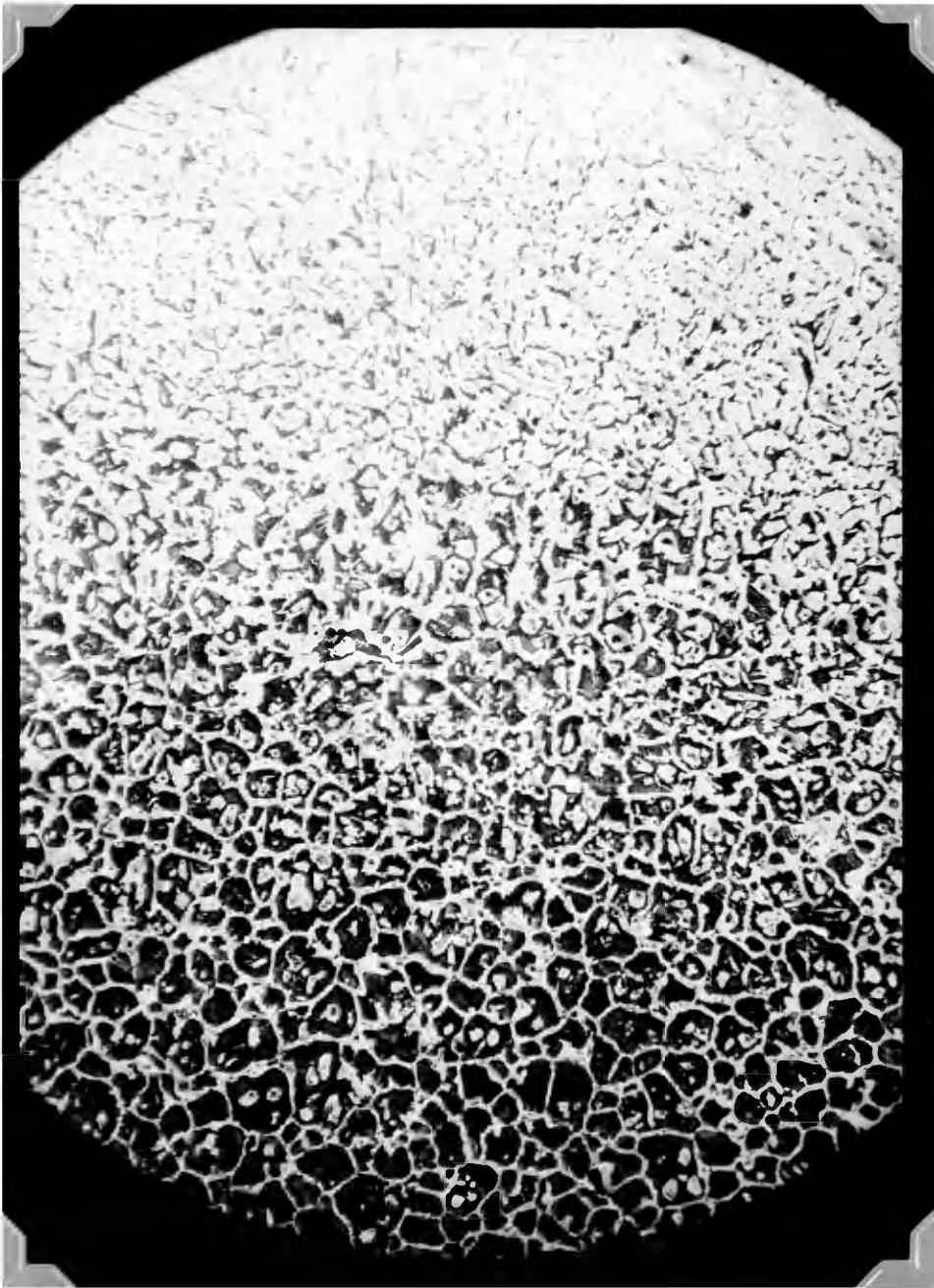
R_A - 59.5

R_A - 61.5

R_A - 60.0

R_A - 61.5

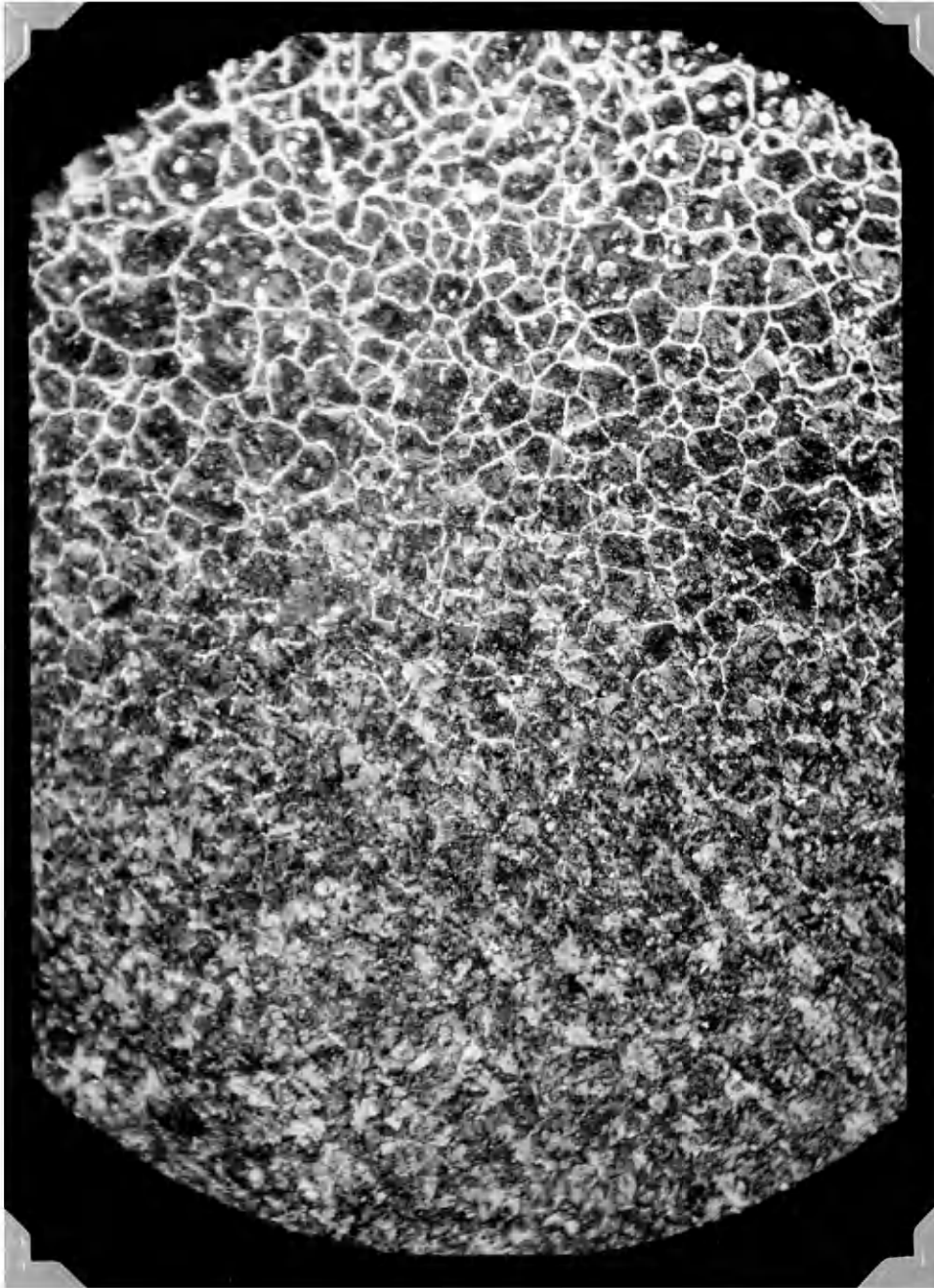
Plate 5.



100X

Picral etched.

Plate 6.



100X

Picral etched.

Plate 7.



100X

Picral etched.

$$\begin{array}{r}
 R_A - 60.5 \\
 R_A - 60.0 \\
 \hline
 \text{Average } R_A - 60.5
 \end{array}$$

Decarburized Gray Iron Sample.--The readings were made from the skin towards the unaltered gray iron at intervals of approximately 1 millimeter:

$$\begin{array}{r}
 \text{Ferritic zone-}R_A-38.0 \\
 \quad " \quad " \quad -R_A-45.0 \\
 \quad " \quad " \quad -R_A-50.0 \\
 \text{Pearlitic zone-}R_A-60.0 \\
 \quad " \quad " \quad -R_A-60.0 \\
 \text{Unaltered Gray Iron-}R_A-60.5 \\
 \quad " \quad " \quad " \quad -R_A-61.5
 \end{array}$$

Fusion Zone of the untreated, welded sample (white cast iron part)

$$\begin{array}{r}
 R_A-73.0 \\
 R_A-74.0 \\
 R_A-73.8 \\
 R_A-74.0 \\
 R_A-74.0 \\
 R_A-74.0 \\
 R_A-73.5 \\
 \hline
 \text{Average } R_A-73.7
 \end{array}$$

Heat-affected zone of the decarburized and welded sample (Hyper-eutectoid steel)

$$\begin{array}{r}
 R_A-67.0 \\
 R_A-68.0
 \end{array}$$

$R_A-67.5$

$R_A-68.0$

$R_A-68.5$

$R_A-67.0$

Average R -67.7

Other areas of the decarburized, and welded sample.

The readings were taken from the filler metal towards the unaltered gray iron at intervals of about 1 millimeter:

Filler metal - $R_A-37.0$

Fusion zone - $R_A-41.0$

" " $R_A-45.0$

Transition zone - $R_A-57.0$

Heat-affected zone - $R_A-67.0$

" " " - $R_A-67.5$

Unaltered gray iron - $R_A-63.0$

Unaltered gray iron - $R_A-62.8$

Dynamic Test

The purpose of this test was to find out at which part of the welded sample failure would occur when the sample was subjected to impact. The method of test was a simple one: it consisted of clamping the welded test piece at one end in a vise, with the weld on one side of the free end, and breaking the free end off by hitting with a hammer on the other end.

The untreated welded sample broke, as was expected, right through the white cast iron structure of the fusion zone.

In contrast, the decarburized welded sample broke off in the unaltered gray iron region instead of through the heat-affected hyper-eutectoid steel zone.

Summary and Conclusions

The research outlined above consisted mainly of decarburization of gray iron by heating in the presence of oxide, then welding the decarburized samples, and finally determination of the properties of the welded samples.

Results may be summarized as follows:

Decarburization of the Gray Iron Samples

Here the term "depth of decarburization" indicates the depth of the decarburized gray iron starting from the skin of a composition and structure corresponding to that of a dead soft steel and extending to the depth where composition and structure correspond to eutectoid steel, and thus covers the whole range of hypo-eutectoid steel. From this experiment, however, it was found that the actual decarburization goes farther than this. Below the hypo-eutectoid region, there is a thicker layer of altered metal of a composition and structure corresponding to eutectoid steel. Therefore, it may be said that when gray iron is decarburized, the surface of the gray iron is replaced by an almost equal depth of steel, varying from hypo-eutectoid steel in the outer layer down to a thicker layer of

eutectoid steel. The depth of this transformed steel depends on the temperature and time of treatment.

(1) The depth of decarburization increases with increase of temperature up to about 1600° F.

(2) The depth of decarburization increases with the time of treatment.

(3) Scaling is the most difficult problem to solve in decarburization. It increases with temperature and with time as well. Sealing off the air during treatment by the method described above gives some help but does not solve the problem. More effective sealing might help further.

(4) The decarburized gray iron consisted of tracing from the skin towards the center, hypo-eutectoid steel, eutectoid steel, eutectoid steel with a few graphite "vestiges" and finally unaltered gray iron.

Gas Welding of the Samples

The decarburized samples were welded by oxyacetylene methods. This was done without the precaution of preheating and slow cooling, as is done in salvaging a gray iron casting in the usual way. A satisfactory weld was obtained as revealed by the results of tests made.

Results of Testing

From the photomicrographs, the fused area of the untreated gray iron is seen to be a white cast iron

structure, whereas that of the decarburized gray iron, is a hyper-eutectoid steel structure in the heat-affected zone. Although hardness tests for the fusion zone in the untreated samples and the heat-affected zone in the decarburized samples are not much different, dynamic tests definitely showed that the welded, untreated test piece broke through the fusion zone whereas the welded, treated one failed through the unaltered gray iron region.

That the eutectoid steel structure with graphite "vestige," in the deeper layer of the decarburized sample changed over into hyper-eutectoid steel structure after welding was probably due to the absorption of graphite "vestiges" not yet completely removed, such as those shown in the upper part of Plate 1.

Should a quicker process for decarburization be available, this might be a most promising way of solving the problem of welding gray iron castings.

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