AN INVESTIGATION OF GRAIN-SIZE, NORMALITY AND ABNORMALITY IN STEEL

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INTRODUCTION

Until H. W. McQuaid and E. W. Ehn presented, in February, 1922, their paper entitled "Effect of Quality of Steel on Case-carburizing Results",(1) it was usually assumed that a chemical specification and certain physical tests were sufficient to determine the suitability of a steel for a particular application. Their work and paper was prompted by the fact that two steels, which for all practical purposes, had identical chemical compositions would and did produce radically different final structures and physical properties after case-carburizing and hardening.

Their work led to the present day McQuaid-Ehn Test for grain size determination. Basically this test consists of subjecting a piece of steel to a carburizing treatment at 930° C for a period of time long enough to develop a hypereutectoid zone of sufficient depth to be studied at X 100 magnification. The material is then cooled slowly enough to develop a pearlitic structure with free cementite outlining the prior austenite grain boundaries. Having this structure the prior austenite grain size of the particular steel can be readily determined and this in turn may be associated with the results to be expected in the heat treatment of the steel.

Closely allied with the prior austenite grain size is the so called "normal" and "abnormal" structures found in steel. After the McQuaid-Ehn test the "normal" structure consists of fine lamellar pearlite entirely surrounded by thin smooth carbide envelopes which definitely delineate the grain boundaries. "Abnormal" steel, by contrast, has very thick carbide envelopes, with coarse pearlite, if any, separated from the carbide by a wide band of ferrite. In many cases the carbide is to a great extent spherodized. Between these two extreme structures there can be found in steel, structures which represent varying degrees of the "normality-abnormality" condition. In general, although by no means in every instance, fine grain size and "abnormality" seem to occur together in steel. A steel which by the McQuaid-Ehn test is "abnormal" will after hardening have soft spots on the case and the steel is not acceptable for case hardening applications.

Originally the McQuaid-Ehn test was developed to detect "abnormal" steel which was not suitable for case hardening. When grain size became important the test was ideally suited for this purpose.

The difference between fine and coarse grained steels is dependent upon their behavior when the steel is heated through the critical range. As a steel is heated through the critical range recrystallization takes place and at a temperature immediately above the critical range, the grains in the steel are very small. On heating to higher temperatures, the steels may be divided into the so called coarse grained and fine grained steels depending on their behavior. In coarse grained steels the grain size is proportional to the temperature to which the steel is heated within the austenitic region, that is to the temperature above the A_3 point. So called fine grain steels resist this grain growth until a temperature known as the coarsening temperature is exceeded. Just above the coarsening temperature the grains of austenite grow rapidly and quickly assume approximately the size normal for the coarse grain steels at this temperature. Any steel which will resist this grain growth at 930° C is classified as a fine grain steel. If coarsening occurs prior to this temperature the steel is classified as coarse grained steel. This temperature of 930° C was arbitrarily selected because practically all commercial heat treating operations are conducted at temperatures not in excess of this temperature.

The advantages and the disadvantages of the two types are summarized by Bain and Vilella (20) in the following table:

EFFECTS OF PREVIOUSLY EXISTING AUSTENITE GRAIN SIZE

Property	Trends in Heat Treated Steel Products	
	From Coarse Grained Austenite (No. 5 and Above)	From Fine Grained Austenite (No. 5, 5 to 8)
Hardenability	Deeper Hardening	Shallower Hardening
Toughness at same Hardness	Less Tough	Tougher
Distortion	More Distortion	Less Distortion
Quenching Cracks	More Prevalent	Usually Absent
Grinding Cracks	More Susceptible	Less Susceptible
Residual Stress	Higher	Lower
Retained Austenite	More	Less
	For Annealed and Normalized Products	
Machinability	(Rough) Better	(Rough) Inferior
Machinability (Special Cases)	(Fine Finish) Inferior	(Fine Finish) Better
Formability (Special Cases)	Superior	Inferior

Further work since McQuaid and Ehn's original paper has indicated that many of the characteristics of steel, as will be noted in the previous table, are closely related to the prior austenite grain size. While the original McQuaid-Ehn test was developed to select suitable heats of steel for case carburizing, it is today used as a control test for many other applications where grain size is important, such as alloy steels and tool steels. Thus, today, when a customer places an order for steel with the mill he may in addition to specifying chemical composition and physical properties require that the steel meet a certain grain size requirement for his particular application.

The exact mechanism by which austenite grain size is controlled in steel is the purpose of this investigation.

THE PROBLEM

This investigation was instituted in an attempt to determine "What is the Cause of Fine Grain in Steel." Much work has been done on this problem since McQuaid and Ehn (1) presented their original paper in February, 1922. With all of the work since that time there is still a great deal of uncertainty as to why a steel does become fine grained by the McQuaid-Ehn test when approximately 1 to 2-1/2 pounds of aluminum is added per ton immediately before the liquid steel is cast into the ingot molds. The methods for controlling grain size in steel have been known and utilized for some time, but no one theory has been generally accepted to completely explain why and how these methods work.

One theory which has been advanced and which is the more commonly held and accepted view is that sub-microscopic non-metallic particles, either nitrides, carbides, or refractory oxides such as aluminum oxide or a combination of these are formed in the liquid steel which act as nuclei for grain formation when the steel is reheated to above the critical range and that these sub-microscopic particles act as obstructants or keys to grain growth.

Another theory is that metallic aluminum in solid solution influences the behavior of the carbides in some manner and thereby restrains grain growth to produce fine grained steels.

Still another view holds that the control of the deoxidation procedure in steel manufacture governs the grain growth characteristics of a steel.

Thus it is seen that no general agreement has been reached as to exactly how aluminum does act to produce a fine grained steel. Previous work has not clearly indicated which or what is the exact mechanism for controlling grain size in steel.

A secondary reason for this investigation was to determine the suitability of making steel from "pure" iron powders by pressing and sintering the powder, and then introducing the carbon to make steel by carburizing the compacts after the sintering operation. Additions of other alloying ingredients such as aluminum, manganese, and silicon it was believed could be more readily controlled using powders instead of melting and casting the metal.

METHOD USED IN THIS INVESTIGATION

In many previous studies commercial heats of steel were used in the experiments which introduced so many variables that no clear cut conclusions could be reached. Therefore it was decided in this investigation to use fairly pure raw materials in an effort to reduce the variables insofar as possible. Also, in order to eliminate possible contamination and other experimental difficulties introduced by melting and casting practice it was decided to press pure iron powder into shape, sinter and carburize the pressed compacts to produce a pure steel.

Electrolytic iron powder manufactured by Plastic Metals Company, Johnstown, Pennsylvania, was used throughout this work. A typical analysis of this powder is:

Element	Per Cent
Total iron	99.910
Total carbon	0.015
Manganese	0.007
Phosphorus	0.004
Silicon	0.007
Sulfur	0.008
Copper	0.010
Chromium	0.002
Nickel	0.015
Molybdenum	0.002
Vanadium	0.003

Element (Cont'd)	Per Cent (Cont'd)
Cobalt	0.007
Tin	0.005
Aluminum	0.002
Arsenic	Nil
Lead	Nil
Mercury	Nil

According to the supplier the particular sample of iron powder used for this investigation contained 0.59% oxygen as determined by a loss of weight after deoxidation in hydrogen. As a check, two 15 gram samples of this powder were deoxidized at 600° C for 2 hours in hydrogen. The powder was taken through the above cycle twice. After the second deoxidation the loss in weight amounted to 0.57% for one sample and 0.50% for the other sample. It is probable that nearly all of this oxygen is present in the form of surface oxide and therefore the iron content in the preceding analysis would be lower by this amount.

The nitrogen content was not determined but the supplier of the powder indicated that it is probably of the order of 0.0001%.

Reynolds chemically pure unpolished standard varnish aluminum powder was used in those compacts which had aluminum incorporated in them. In some compacts the aluminum powder was added prior to the deoxidation of the iron powder under hydrogen and in other cases the aluminum powder was added after the iron powder had been deoxidized. In either case 2-1/2 pounds of aluminum powder was added per ton of iron. This amounts to 0.125% aluminum. The various powder samples were placed in a clean glass mason jar with quartzite balls and thoroughly mixed and ground by revolving the jar at low speed in a lathe for two hours.

Compacts were made by pressing the powders with a hardened steel punch into a hardened steel die under 50 tons p.s.i. with a hand operated hydraulic press. The compacts were 0.517" in diameter and approximately one-half of an inch long.

Three compacts were checked and the density was found to be between 7.22 and 7.41 after the sintering operation. After cold working under the hydraulic press, a density of 7.73 was obtained for one compact. This compares favorably with 7.80 to 7.84 for most steel.

Later in the paper, under Results and Discussion, each powder and the case history of each compact will be clearly outlined for thorough clarification and for studying the included photomicrographs.

Before compacting, certain of the powders were deoxidized in hydrogen for 2 hours at 600° C. The hydrogen was generated in a Kipps Generator with zinc using a 1 to 4 concentration of sulphuric acid (H_2SO_4). The hydrogen was passed through a dryer containing calcium chloride ($CaCl_2$) and thence through a dryer containing phosphorus pentoxide (P_2O_5) dusted onto glass wool. Finally the hydrogen passed through a tube of glass wool before entering the furnace. A Burrell high temperature electric tube furnace was used for deoxidizing the powder, sintering and carburizing the compacts. During the deoxidation and sintering operations the powder and the compacts were placed on clean sheet metal boats, the boats being placed inside of a thoroughly cleaned nickel-chromium tube for the necessary heating cycles. Both ends of the metal tube were beveled to the correct taper on the inside diameter to produce a tight fit with a rubber stopper. The rubber stoppers were equipped with glass tubes and the necessary stop cocks to control the flow of gas through the tube. Carburizing was carried on in one tube while another tube was reserved and used only for the deoxidation and sintering cycles. Temperature in the furnace was controlled by means of a rheostat and the temperatures were read with a Leeds and Northrop potentiometer using a chromel-alumel thermocouple.

Before the actual furnace operations were performed a calibration curve of inside tube versus outside tube temperatures was obtained to determine the temperature differential inside the furnace tube. Knowing this temperature differential, thereafter the furnace temperature was controlled by placing the thermocouple outside of and in contact with the furnace tube since this eliminated complications of putting the thermocouple leads through one of the rubber stoppers.

A Cenco Hyvac Pump guaranteed by the manufacturer to give a vacuum of 0.30 micron or better was used to evacuate the tube before the deoxidizing and sintering operations were carried out. On each run the system was filled and evacuated three times with hydrogen before the furnace was turned on. After flushing the third time with hydrogen the system was filled with hydrogen and the furnace turned on. By means of a valve a small amount of hydrogen was released from the system during the entire time of the deoxidizing and sintering operations, thus keeping a fresh atmosphere of hydrogen in the system at all times. With those compacts which were sintered in vacuo, the system was evacuated for ten minutes before the heat was turned on, and the system was evacuated throughout the entire heating and cooling cycle. The sintering operation was carried out at 1100° C for two hours at temperature on all compacts. In both the deoxidizing and sintering operations the material was given a furnace cool.

Before carburizing, some of the compacts were cold worked on the end and sides to increase the density of the compact and thereby insure that a hyper-eutectoid zone would be built up on the surface and prevent excessive carbon penetration to the core. For carburizing the compacts were packed in a commercial solid carburizer in the nickel-chromium tube and sealed at both ends with a rubber stopper equipped with a glass tube. A positive pressure of carbon dioxide (CO_2) was maintained on the system with a Kipps Generator using high grade marble and a 1 : 3 concentration of hydrochloric (HCl) acid. Before the carbon dioxide (CO_2) entered the furnace tube it was bubbled through a water bottle and thence through a dryer containing calcium chloride ($CaCl_2$) covered with glass wool. The carburizing cycle was 24 hours at 930° C. All carburized specimens were given a furnace cool to room temperature.

After the carburizing treatment the compacts were mounted in bakelite and 3/16 of an inch machined off of the end before starting the polishing operation. It was considered desirable to machine this amount off in order to get below the "corner effect" of the carburizing operation. Each compact was polished on a fine abrasive wheel followed by successive polishing on No. 1, 1/2, 0, 00, and 000 emery paper. The specimen was rotated 90° between each paper. Final polishing was accomplished on a rotating disc covered with cotton flannel using a water suspension of 600 alundum flour. The polishing disc rotated at between 250 and 300 r.p.m. A 2% nital solution was used to etch the specimens after the polishing operation.

All photomicrographs were made with a Bausch and Lomb ILS Metalloscope with a type G camera attached. The source of illumination was a 4.5 ampere carbon arc. The photomicrographs were made at 100 diameters. This magnification was achieved by the use of a 16 mm. achromatic objective and a 7.5 mm. hyperplane eyepiece with the ground glass at 30 centimeters. Eastman commercial ortho 4" x 5" sheet film was used and developed in Eastman developer 61A. The prints were made on F4 paper using D72 developer.

RESULTS AND DISCUSSION

Before discussing the results, it is desirable to outline in detail the various powder samples used and the history of the compacts studied in this investigation.

Powder samples were coded by numbers as follows:

Sample No. 0 — Plast-iron powder grade A11 - A10 from the can as received. Not deoxidized.

Sample No. 1 — Plast-iron powder grade A11 - A10 with 2-1/2 pounds of Reynolds unpolished standard varnish aluminum powder added per ton of iron powder. This powder was not deoxidized.

Sample No. 2 — Same as powder sample No. 1 except that the powder was deoxidized as described previously in an atmosphere of hydrogen for 2 hours at 600° C. Deoxidation carried out after the aluminum powder was added.

Sample No. 3 — Plast-iron powder grade A11 - A10 deoxidized before adding 2-1/2 pounds of Reynolds unpolished aluminum powder per ton of iron powder.

Sample No. 4 — Plast-iron powder, grade A11 - A10, deoxidized under an atmosphere of hydrogen for 2 hours at 600° C.

After compacting all compacts were sintered for 2 hours at 1100° C followed by carburizing in a commercial carburizing compound for 24 hours at 930° C. All compacts were sintered in an atmosphere of hydrogen, except those so noted in the list of compacts coded by numbers as follows:

Compact No. 1 — Powder sample No. 0.

Compact No. 2 — Powder sample No. 4. Compact cold worked with a hammer after sintering.

Compact No. 3 — Powder sample No. 4.

Compact No. 4 — Powder sample No. 2. Compact cold worked with a hammer after sintering.

Compact No. 5 — Powder sample No. 2.

Compact No. 6 to 10 inclusive — Powder sample No. 2. These compacts will not be discussed in this paper because the structures were the same as Compact No. 5 and would therefore merely be repetition.

Compact No. 11 — Powder sample 0.

Compact No. 12 — Powder sample 0, cold worked with a hammer after the sintering operation.

Compact No. 13 — Powder sample No. 3.

Compact No. 14 — Powder sample No. 3, cold worked with a hammer after sintering.

Compact No. 15 — Powder sample 0, sintered in vacuum.

Compact No. 16 — Powder sample 0, sintered in vacuum, and cold worked with a hammer after the sintering operation.

Compact No. 17 — Powder sample No. 1, sintered in vacuum.

Compact No. 18 — Powder sample No. 1, sintered in vacuum, and cold worked with a hammer after sintering.

Table 1 lists in tabular form the pertinent information about the various compacts.

Under the column labelled "normality", table 1, the following code was used to distinguish the degrees of abnormality recognized in the various compacts:

A = Slightly abnormal

B = More abnormal

C = Very or most abnormal

This code of abnormality was based on the appearance of the structure at 100 magnifications. By "slightly abnormal" is meant a structure with cementite, very little ferrite and a fairly recognizable structure of pearlite. A "more abnormal" structure is one with less pearlite and wider bands of ferrite. The "very or most abnormal" structure consisted almost wholly of ferrite and cementite. Very little, if any, pearlite could be found in specimens labelled "C" in the column head "abnormal."

Under the heading austenite grain size, the only distinction made is "coarse" or "fine." In practically all cases in this investigation the structures were so abnormal as to preclude the assignment of a definite grain size number with any degree of accuracy.

The results of this investigation are:

That pure powders can be mixed, compacted, sintered, and carburized satisfactorily to produce steel of a given composition.

That an abnormal structure is obtained in a "pure" iron-carbon alloy and in a "pure" iron-carbon-aluminum alloy when pack caburized by the McQuaid-Ehn procedure. The structure seems to be most abnormal in those cases where the pure iron powder was compacted, sintered, and carburized without previously deoxidizing the powder under hydrogen. This is especially noted in compacts Nos. 1 and Nos. 12,both of which are very abnormal and were compacted without deoxidizing the iron powder sample. Compact No. 12 was cold worked after the sintering operation whereas compact No. 1 was not. It would seem safe to assume that some deoxidation of the compact takes place

TABLE 1

Compact Number	Powder Number	Aluminum Addition Before or After Deoxidation			Deoxidized		Cold Worked		Sintering		Carburized Hrs.	Normality		Austenite Grain Size	
		Before	After	No Al.	Yes	No	Yes	No	H_2	Vac.		Norm.	Abnorm.	Coarse	Fine
1	0			x		x		x	x		24		C		x
2	4			x	x		x		x		24		C		x
3	4			x	x			x	x		24		B		x
4	2		x		x		x		x		24		B		x
5	2		x		x			x	x		24		B		x
6	2		x		x				x						
7	2		x		x				x						
8	2		x		x				x						
9	2		x		x				x						
10	2		x		x				x						
11	0			x		x		x	x		24		C		x
12	0			x		x	x		x		24		C		x
13	3	x			x			x	x		24		B		x
14	3	x			x		x		x		24		B		x
15	0			x		x		x		x	24		A		x
16	0			x		x	x			x	24		A		x
17	1					x		x		x	24		A	x	
18	1					x	x			x	24		A	x	

during the sintering operation at 1100° C for 2 hours. However, it would be expected that this deoxidation would not be as thorough as with those compacts made from powder which had been deoxidized previous to the compacting operation. Then, too, the compacts which were fabricated from deoxidized powder were also subjected to the same sintering operation. It can, therefore, be seen that they were probably more thoroughly deoxidized than those which relied entirely on the sintering operation for deoxidation. A survey of table 1 indicates that the most abnormal structures were obtained in those compacts made from powders which had not previously been deoxidized under hydrogen.

Previous work (2) has indicated that for a pure iron-carbon alloy an abnormal structure results during pack carburizing, but that a normal structure is the result when the alloy is carburized in an oxygen free hydrogen-hydrocarbon atmosphere. However, the evidence to support this statement is somewhat weak since "pure" iron from six of seven different sources showed some abnormality even in oxygen free carburizing. One of the six abnormal structures was not quite so abnormal as were the other five. "Pure" iron from one source only produced a completely normal structure when carburized in a hydrogen-hydrocarbon atmosphere.

Other work (3) presents evidence that a "pure" iron-carbon-aluminum alloy behaves likewise under pack carburizing and under an oxygen free hydrogen-hydrocarbon atmosphere. This implies that oxygen free carburizing must obtain in order to get a normal structure in "pure" alloys of iron-carbon and in "pure" iron-carbon-aluminum alloys.

If as indicated in these previous papers abnormality is the result of oxygen during pack carburizing, why then should not all compacts in this investigation exhibit the same degree of abnormality? Since the pack carburizing treatment of the compacts for this investigation were all carried out for 24 hours at temperature, it seems reasonable to conclude that the cycle was of sufficient duration to "oxidize" the compacts to the same degree and therefore the same degree of abnormality should exist in all compacts. This, however, is not the case, for all degrees of abnormality were found to exist in the various compacts. Furthermore, it is somewhat difficult to conceive of oxygen being absorbed by the iron compacts treated in a compound since carburizing in itself requires the absorption of carbon which is basically a reducing operation. In addition if the absorption of oxygen takes place when carburizing in compound why then are not abnormal structures produced in every instance when carburizing in compound?

These questions make for interesting speculation and the results of this work do not lend enough information to conclusively answer them. Further work and experimental data will need to be performed and collected to satisfactorily explain the anomalies.

An interesting observation of the photomicrographs is that in the most abnormal structures 90 to 95% of the cementite is concentrated around the voids in the compacts. (See Photomicrographs Nos. 1 and 12). Very few, if any, voids are located in the wide bands of ferrite. Since the solid metal compacts for this investigation were shaped from powders by pressing, the density is lower and the number of voids greater than in comparable rolled or hot worked metal. The concentration of the cementite around the voids or the voids in the cementite is especially pronounced in the very abnormal structures consisting almost completely of cementite and ferrite. It is questionable as to exactly how to interpret this phenomena of the voids being almost entirely concentrated in the cementite. It might possibly be explained by the fact that the voids are areas of oxygen segregation. Or it may be that the voids provide passage ways for the gas carrying the carbon into the specimen to form cementite and the cementite did not diffuse throughout the specimen. However, in the less abnormal specimens the voids did not appear to be concentrated in the cementite and the voids did not show up as pronouncedly when examined under the microscope after the polishing operation. The final polishing of the non-deoxidized iron powder on the 600 alundum wheel was considerably more critical than the other compacts because of the apparent tendency to exaggerate the voids as observed under the microscope.

A survey of the structures after pack carburizing indicates that the degree of abnormality in the specimens remains approximately the same whether the aluminum was added before or after the iron powder was deoxidized under hydrogen. Photomicrographs of compact No. 4 and compact No. 14 show approximately the same degree of abnormality. These two compacts were subjected to the same treatment procedure except that in compact No. 4 the aluminum powder was added before the iron powder was deoxidized while for compact No. 14 the aluminum powder was added after the iron powder was deoxidized under hydrogen for 2 hours at 600° C.

Another interesting observation is that compacts 15, 16, 17, and 18 which were sintered under vacuum consistently showed the least abnormal structure after pack carburizing. Compacts 15 and 16 were pressed from the iron powder without previous deoxidation. Compacts 17 and 18 were pressed from iron powder with 2-1/2 pounds of aluminum per ton of iron without any previous deoxidation. Photomicrographs of compacts Nos. 16 and 18, the cold worked specimens are included in this paper. Compacts 15 and 17 were identical in composition except that they had not been cold worked and therefore the carbon penetrated deeper thereby not delineating the hypereutectoid zone as clearly. This trend in the direction of normality may indicate that hydrogen in solution is a contributing factor in causing "pure" oxygen free iron to become abnormal during pack carburizing. Further work will be required to clarify this observation.

CONCLUSIONS

Without making unsupported assumptions, it is believed that the following conclusions may be drawn from this investigation.

1. Satisfactory steel specimens can be produced by compacting, sintering, and carburizing "pure" iron powders.

2. An abnormal structure is obtained in a "pure" iron-carbon alloy and in an iron-carbon-aluminum alloy when pack carburized by the McQuaid-Ehn test. This seems to be true whether the iron powders were deoxidized or not before the carburizing treatment. However, the abnormality is most pronounced when using powder which had not been deoxidized, and which had been sintered in hydrogen. Using the same powder and sintering in vacuo gave a less abnormal final structure after pack carburizing.

3. There is some reason to believe that hydrogen is a contributing factor in causing an abnormal structure in the alloys studied in this investigation.

4. The cementite formed during pack carburizing tended to concentrate around the voids in the pressed compacts.

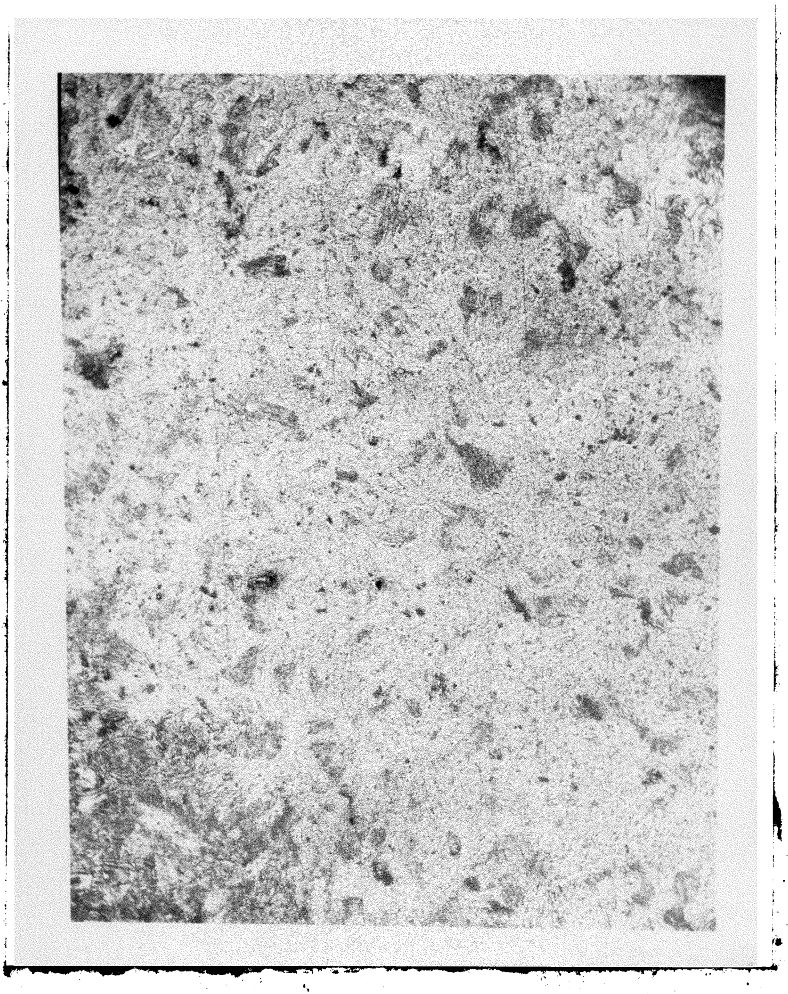
5. The evidence does not indicate that oxygen is the sole cause of abnormality during pack-carburizing.

Compact No. 1. X 100

Structure consists wholly of cementite and ferrite. Note concentration of voids in the cementite and how the voids seem to be exaggerated by the polishing operation.

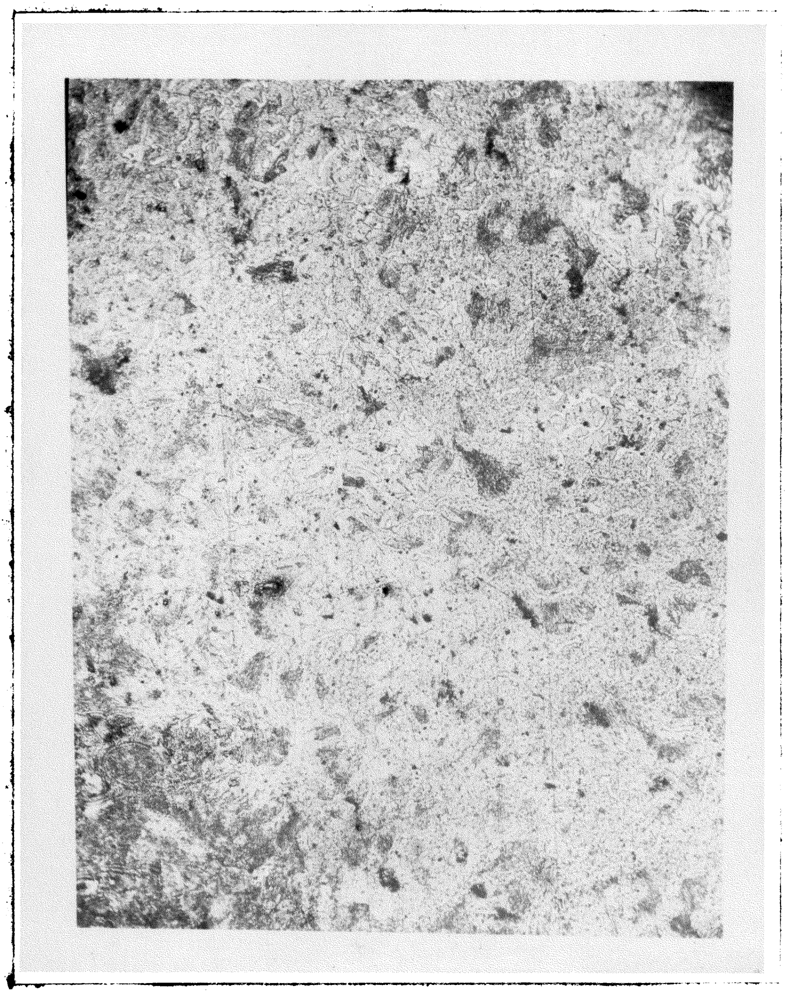
Compact No. 2. X 100

Structure consists of ferrite, cementite and pearlite.



Compact No. 4. X 100

Note that the structure is less abnormal than compact Nos. 1 and 2.

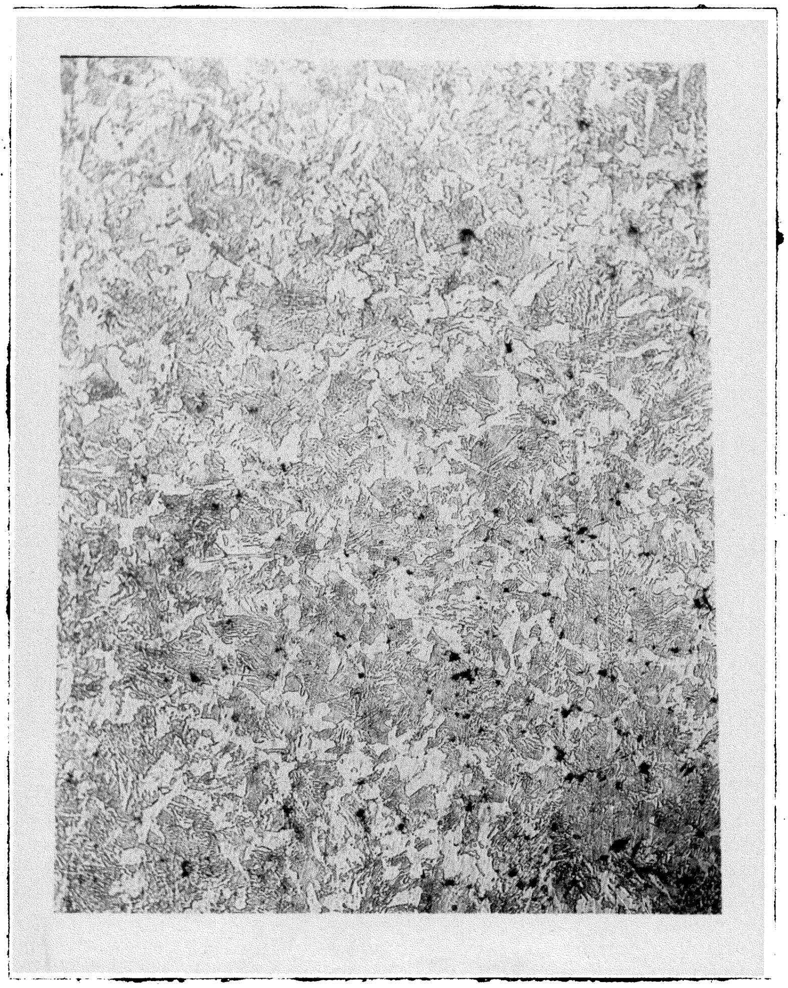


Compact No. 12. X 100

Note again the very abnormal structure consisting solely of cementite and ferrite with the cementite concentrated around the voids. Again the voids were exaggerated by polishing.

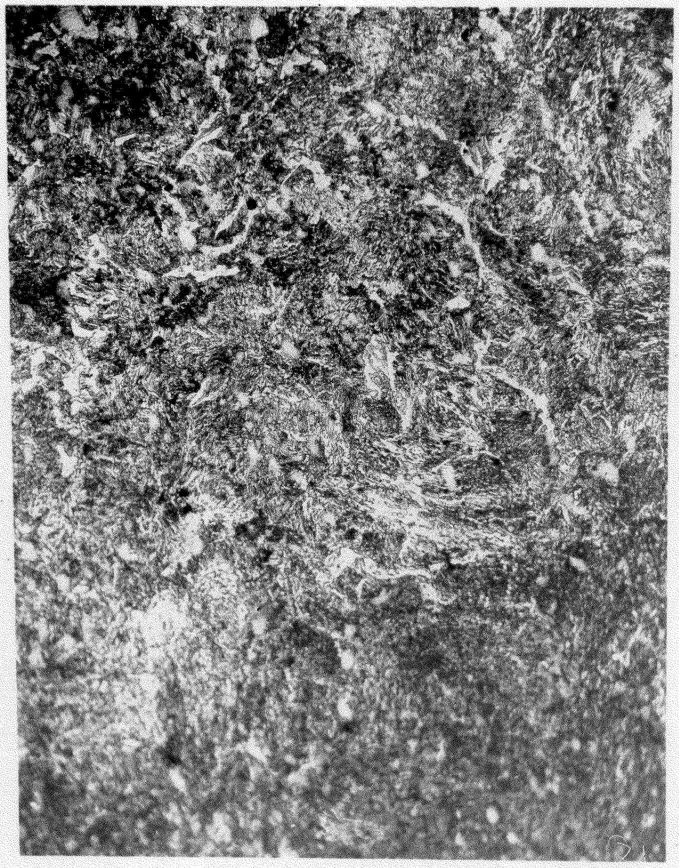
Compact No. 14. X 100

Structure consists predominately of ferrite and cementite with some pearlite.



Compact No. 16. X 100

Structure consists of ferrite, cementite and pearlite. Compare this structure with compacts Nos. 1 and 12, which were processed in the same manner except that compact No. 16 was sintered in vacuum.



Compact No. 18.   X 100

Structure consists of cementite, ferrite and pearlite.

SUGGESTIONS FOR FUTURE INVESTIGATION

1. Make and study compacts fabricated from iron powder which has been deoxidized under hydrogen followed by a period of heating in vacuo, thereby attempting to get oxygen free, hydrogen free compacts. Carburize some compacts in a hydrogen-hydrocarbon atmosphere and other compacts by pack carburizing. This could be done with various combinations using iron alone and iron with aluminum added.

2. Make up and study some compacts with various amounts of manganese added before and after deoxidation of the iron powder in an effort to determine whether alloying elements of the deep hardening type contribute to normality when the compacts are pack carburized.

3. Carry out the carburizing with a hydrogen-hydrocarbon gas to determine difference in structures when compared with pack carburizing.

4. Investigate varying amounts of aluminum added to the iron up to about 3% aluminum.

5. Sinter various combinations of oxygen free, hydrogen free compacts in an atmosphere of nitrogen followed by pack carburizing some compacts and carburizing other compacts in hydrogen-hydrocarbons.

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Wilton F. Melhorn

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