RP 14

STEEL FOR CASEHARDENING—NORMAL AND ABNORMAL STEEL

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ABSTRACT

That soft spots in casehardened articles may be due to the kind of steel used, as claimed by McQuaid and Ehn, has been experimentally confirmed. The characteristics of the so-called normal and abnormal microstructures of the extreme types and intermediate gradations are described. On quenching in water structurally abnormal steel proved more prone to give soft spots. However, by quenching in brine or other drastic quenching media uniformly hard cases were obtained in structurally abnormal steel as well as in normal steel. Air or other gases which are usually dissolved in quenching water may cause soft spots. After carburizing, the core of abnormal steel, most probably because of its finer grain, had higher impact strength than normal steel. Most cases of abnormality in commercial steel seem to be associated with the use of aluminum for deoxidizing, although abnormal steel can also be produced in other ways. Nothing arose during the progress of the investigation to disprove Ehn's theory that abnormality is ordinarily chiefly due to the presence of oxides, perhaps dissolved but more probably undissolved.

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I. INTRODUCTION

In 1922 it was pointed out [1] that soft spots in casehardened articles might be due to the quality of the steel used and not simply to incorrect practice in the carburizing and hardening operations, as might on first thought be assumed. Having noticed in a large roller-bearing plant that soft spots generally occurred only in certain heats of steel, McQuaid and Ehn discovered that these heats showed peculiar microstructural features after carburizing, although otherwise nothing amiss could be detected by the usual chemical or mechanical tests. They became convinced that steel of the peculiar microstructure to which they gave the rather ill-chosen name, "abnormal steel," could not in the ordinary routine of their commercial practice be hardened without soft spots. They also advocated framing specifications whereby steel having an "abnormal" structure in what has become known as the "McQuaid-Ehn carburizing test" would be rejected for casehardening. Ehn ventured the explanation that abnormality in steel is due to oxides, either in solution or as submicroscopic (colloidal) particles.

From the first, considerable skepticism was expressed both as to the conclusion that "abnormal" steel was a cause of soft spots and as to the explanation that "abnormality" was due to oxides in the steel. Most steel manufacturers did not at first believe the steel was to blame for soft spots and objected to including the McQuaid-Ehn test in specifications. On the other hand, many makers of casehardened parts, particularly automobile manufacturers, seemed certain that much of their trouble with soft spots was due to "abnormal" steel. There is still some controversy over the subject, and some metallurgists even yet doubt the existence of abnormal steel. However, in the past few years the McQuaid-Ehn carburizing test has been used widely in steel mills and by carburizers as

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[1] E. W. Ehn, "Influence of dissolved oxides on carburizing and hardening qualities of steel," J. Iron and Steel Inst., **105**, p. 157; 1922. W. H. McQuaid and E. W. Ehn, "Effect of quality of steel on case-carburizing results," Trans. Am. Inst. Min. and Met. Engrs., **67**, p. 341; 1922. E. W. Ehn, Irregularities in casehardening work caused by improperly made steel," Trans. Am. Soc. for Steel Treat., **2**, p. 1177, 1922. E. W. Ehn, "Causes of failures in casehardening steel," Iron Age, p. **109**, p. 1807; 1922.

a check on the suitability of the steel for casehardening.[2] The McQuaid-Ehn test has also come into vogue as a supplement to the other metallographic methods. Weber,[3] for example, carburized electric welds made in different atmospheres and found variations in the carburized structures according to the atmosphere used. Wright[4] carburized tool steels to see whether there was any relation between the life of cold-forming tools and the carburized structure of the tools; he found no obvious relation, however.

When requested by several automobile companies to study the "abnormal steel" problem, the Bureau of Standards undertook the study both because of its practical importance and because the fundamental question of quality in steel was involved. It was the aim in this work to determine by laboratory tests whether or not abnormal steel is more prone to give soft spots when hardened after carburization and, if an affirmative answer was obtained, to attempt to ascertain more definitely the cause or causes of abnormality, since an understanding of the causes might allow users to adopt some commercially practicable solution of this phase of the problem of soft spots in casehardening.

The terms "normal" and "abnormal," which have gained currency in this connection, are very inapt; they tend to carry the connotation of good and bad and are also likely to be confused with the term "normalized," which relates to a well-recognized heat treatment. It must be emphasized that by normal or abnormal steel is not meant superior or inferior steel. The terms have been retained for the lack of better ones and are here used in a very restricted technical sense to indicate certain structural characteristics of carburized steel.

II. CHARACTERISTICS OF THE NORMAL AND ABNORMAL STRUCTURE

1. EXTREMES OF NORMALITY AND ABNORMALITY

From McQuaid and Ehn's work, one can hardly dispute that, by carburizing, differences in structure are brought out between steels that otherwise appear to be alike. On the basis of these structural differences, the steel is classed as "normal" or "abnormal." In carrying out the McQuaid-Ehn test the sample is carburized at about 940° C. (1,725° F.) until a thick carburized layer is obtained with a well-defined hypereutectoid zone and is then slowly cooled. Upon examination under the microscope, differences between normal and

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[2] W. G. Hildorf, "Improvements in automotive steels," Iron Age, **116**, p. 1378 and 1447; 1925. J. Bethune and W. G. Hildorf, "Gear steels and the production of automobile gears," J. Soc. of Auto. Engrs., **19**, p. 422; 1926.

[3] L. J. Weber, "Studies on electric welding," Trans. Am. Soc. for Steel Treat., **11**, p. 425; 1927.

[4] F. L. Wright, "High-temperature quenching treatment applied to cold-heading ball dies of plain carbon tool steel," Trans. Am. Soc. Steel Treat., **13**, p. 290; 1928.

abnormal steel can be noted in the structure of the core, transition zone, and hypereutectoid zone. The last is usually the most characteristic.

In abnormal steel the grain size is small and the cementite of the hypereutectoid zone is coalesced into thick masses generally surrounded by ferrite. In normal steel the grain size is larger and in the hypereutectoid zone the grains of pearlite are bounded by thin films of cementite. The abnormal structure, therefore, is distinguished by fine-grain size, coalesced cementite, and the presence of a layer of ferrite about the hypereutectoid cementite. These features are generally associated, but not always; some fine-grained specimens show very little coalescence of the cementite, while others of fairly large grain size show pronounced coalescence of the cementite. This will be discussed further under the heading "intermediate gradations." Apparently, the chief feature of the abnormal structure is the lack of perfection in the crystallization of the pearlite, as evidenced by the coalescence of the cementite and its separation from the ferrite. The carburized layer in an abnormal steel is usually thinner than in a normal steel similarly carburized. Figures 1 and 2 show the carburized layers of typical normal and abnormal steel specimens. The characteristics of the normal and abnormal structure are found among the alloy steels as well as in plain carbon steel. Most of the work described in this paper was done on plain carbon carburizing steel of about 0.2 per cent carbon and 0.5 per cent manganese content.

Various kinds of carburizers were tried in the investigation, but the carburizer appeared to play no part in determining the normality or abnormality of the resulting structure. Early in the work a mixture of 60 parts by weight of powdered charcoal and 40 parts barium carbonate was used, but later it was found more convenient to use a commercial carburizer. The carburizing temperature given above must be adhered to fairly closely. If too low a temperature is used, no hypereutectoid zone is produced, while if the carburizing temperature is too high, the structural features of the carburized layer characteristic of abnormal steel become less pronounced, and it becomes difficult to distinguish between the two types.

2. INTERMEDIATE GRADATIONS

Figure 1 illustrates the extremes of structural normality and abnormality in commercial carbon carburizing steel. The differences between the two types are not always so marked, however, there being intermediate gradations, and one is often in doubt as to how to classify a steel according to the McQuaid-Ehn test. Some steel companies have prepared charts showing micrographs of steels classified into as many as 10 grades according to the grain size. These charts give somewhat uncertain information, for, as Gat[5] has pointed out, classification by grain size alone does not give sufficient weight to the important feature of coalescence of the cementite. In plain carbon steel fineness of grain is usually associated with coalescence of the cementite. With alloy carburizing steels, which are widely used, this is not always so, and a very fine-grained steel may show only slight coalescence of the cementite. Figure 3 shows the structure of the carburized layer of a chromium-vanadium steel (C, 0.50 per cent; Mn, 0.80 per cent; Cr, 0.25 per cent; V, 0.18 per cent) with extremely fine grain, but with only slight coalescence of the cementite. The cementite envelopes in the carburized layer of effervescent steel are usually a little thicker than in killed steel, and because of this effervescent steel may be regarded as less normal than killed steel. However, the extreme types of normal and abnormal steel may be readily differentiated in effervescent steel as well as in killed steel.

3. SEGREGATIONS OF ABNORMALITY

It has been observed that there may be "segregations of abnormality." Figure 4 shows the cross section of a bar of effervescent steel; the inner segregate was abnormal, whereas the outer zone was normal. For a complete McQuaid-Ehn test of a given steel it is necessary, therefore, to inspect a full cross section of a bar and different positions of an ingot. What may be called microsegregations of abnormality are also found, abnormal spots and streaks sometimes being present in samples predominantly normal in structure.

4. DEPTH OF CARBURIZED LAYER

The carburized layer in abnormal steel is usually less deep than in normal steel carburized under the same conditions. In order to obtain a roughly quantitative estimate, microscopic measurements of the depth of the carburized layer were made of a number of samples of normal and abnormal steel, carburized under identical conditions (8 hours at 940° C. (1,725° F.) in the same pot). The inner boundary of the carburized layer was taken arbitrarily to be at about 0.75 per cent carbon content, and no difficulty was experienced in getting readings showing close agreement. The arrows in Figure 1 show the depth of carburized layer as estimated in this way. As can be seen in Table 1, the average depth of carburized layer of the normal specimens was about 10 per cent greater than that of the abnormal specimens. The effect of varying the time and temperature on the depth of carburized layer of the two types of steel was not determined. It should be noted that the "special manganese carburizing steel" (C, 0.16 per cent; Mn, 1.36 per cent; P, 0.018 per cent; S, 0.096 per cent; Si, 0.07 per cent), this being a sample of a steel now widely

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[5] J. D. Gat, "Normality of steel," Trans. Am. Soc. Steel Treat., 12, p. 376; 1927.

advertised under a trade name for its ease of machining and uniform hardening, had the thickest carburized layer of any of the specimens. Its structure was normal. The properties of this type of steel will be considered in further detail later.

TABLE 1.—*Depth* [1] *of carburized layer of normal and abnormal steel*

NORMAL

Specimen No.	Chemical composition						Depth of carburized layer
	C	Mn	S	P	Si	Ni	
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Thousanths of an inch*
122	0.14	0.44					42
134	.14	.42					46
146	.12	.43					45
152	.17	.44				0.50	48
55							53
45	.21	.47					55
19M	.12	.37	0.024	0.010	0.063		46
A	.14	.23	.049	.018			50
155	.22	.53	.018	.048	.02		49
Average							48.25
Special Mn carburizing steel J [2]	.16	1.36	.018	.098	.07		59
ABNORMAL							
113	0.14	0.44					42
119	.14	.44					39
125	.14	.42					43
131	.14	.42					44
137	.12	.43					45
143	.12	.43					42
149	.17	.44				0.50	43
56							47
46	.08	.33					41
47	.22	.41					46
13M	.12	.39	0.025	0.012	0.004		42
10M	.12	.34	0.23	.013	.01		42
16T	.13	.37	.027	.010	.008		42
E	.16	.42	.042	.016			46
Average							43.25

[1] See p. 427 for manner of estimating depth.

[2] Material from two different manufacturers was used in the course of the investigation as representative of special manganese carburizing steel. One has been designated "J" and the other "M" throughout this paper.

5. EFFECT OF CONDITION OR TREATMENT OF THE STEEL

(a) MECHANICAL TREATMENT

A question which comes up in classifying a steel by the McQuaid-Ehn test is the effect of the condition or treatment of the steel—whether it is cast, cold-worked, annealed, etc. A few experiments at the Bureau of Standards[6] have indicated that the condition of the steel prior to carburizing generally has little effect on the structure of the carburized layer. A 2-inch round rolled from a 21 by 21 inch normal steel ingot had the same normal structure as the ingot. A one-half inch flat bar cold-rolled from a 1½-inch round normal bar

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[6] S. Epstein, Discussion of W. J. Merten: "Irregular carburization of iron and iron alloys—the cause and prevention," Trans. Am. Soc. Steel Treat., **9**, p. 920; 1926.

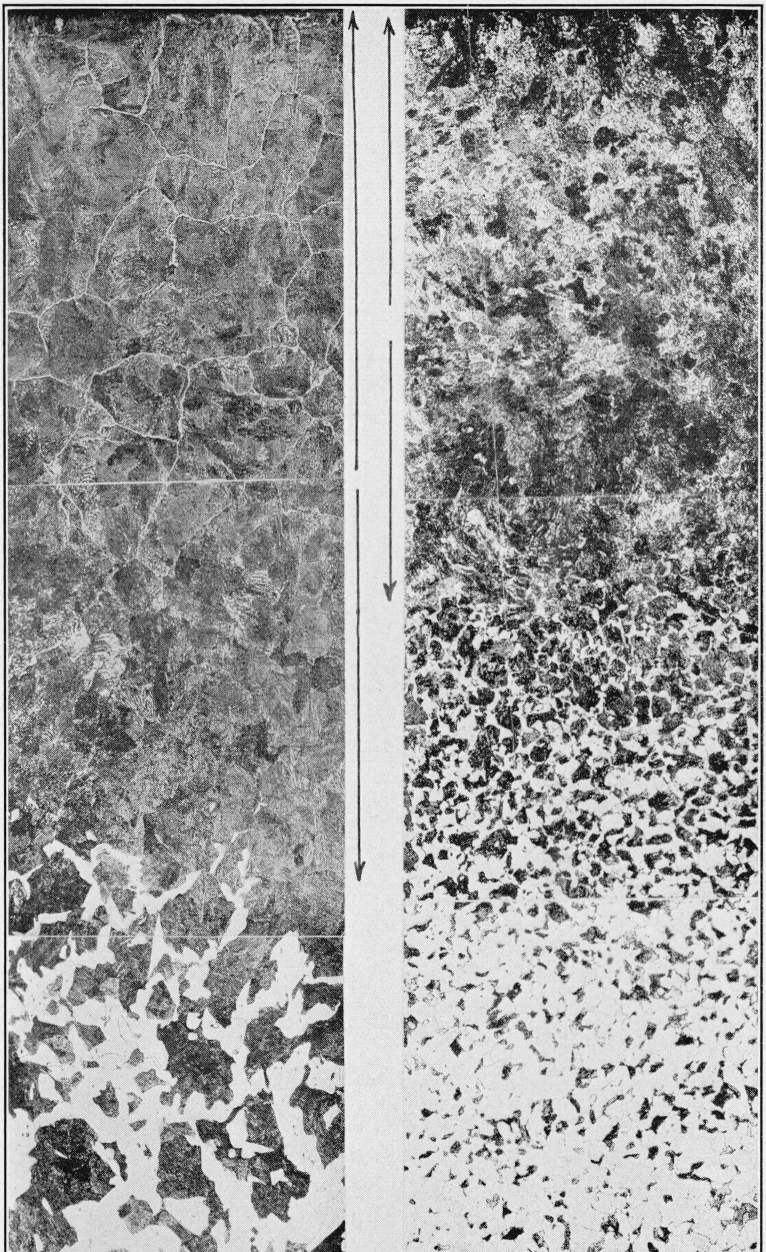

FIG. 1.—*Structure of carburized layers of typical normal and abnormal carburizing steel.* × *100*

The abnormal steel has a finer grain, a shallower case, and shows coalescence of the cementite in the hypereutectoid zone. In all of the micrographs, unless otherwise indicated, the etching reagent was 2 per cent nitric acid in alcohol. The letters, N and A, refer to normal and abnormal, respectively

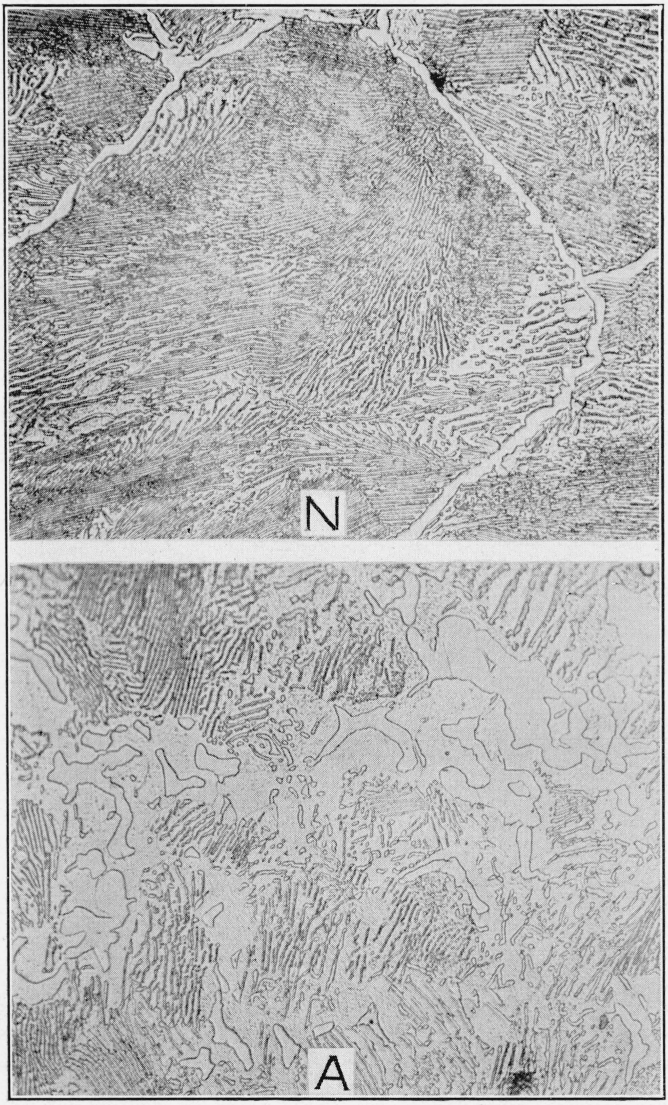

Fig. 2.—*Structure of typical normal and abnormal steel after carburizing.* × *500*

The hypereutectoid zones of the specimens of Figure 1 are shown here at higher magnification. The coalescence of the cementite and its separation from the ferrite in the abnormal steel are very marked. In the normal steel, the pearlite grains are large and well developed, surrounded by thin cementite envelopes

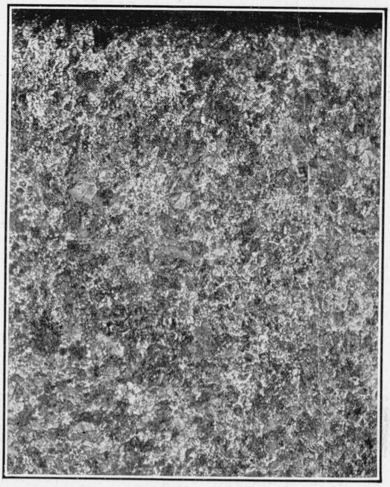

FIG. 3.—*The carburized layer of a chromium-vanadium steel.* × *100*

The grain is very fine, but there is no pronounced coalescence of the cementite

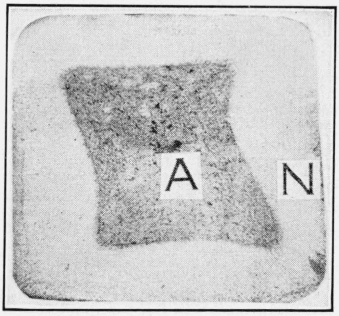

FIG. 4.—*Segregation of "abnormality."* × *1*

A cross section of the bar was deeply etched with hot 1: 1 hydrochloric acid. The carburized structure of the inner segregate was abnormal; the outer zone was normal

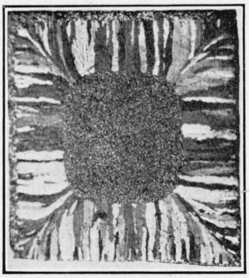

FIG. 6.—*Effect of annealing in hydrogen on abnormal steel.* × 3

Etchant, aqueous ammonium persulphate

Cross section of a specimen of abnormal carburizing steel annealed in hydrogen at 830° C. for 24 hours; the outer coarsely crystalline zone was apparently completely decarburized

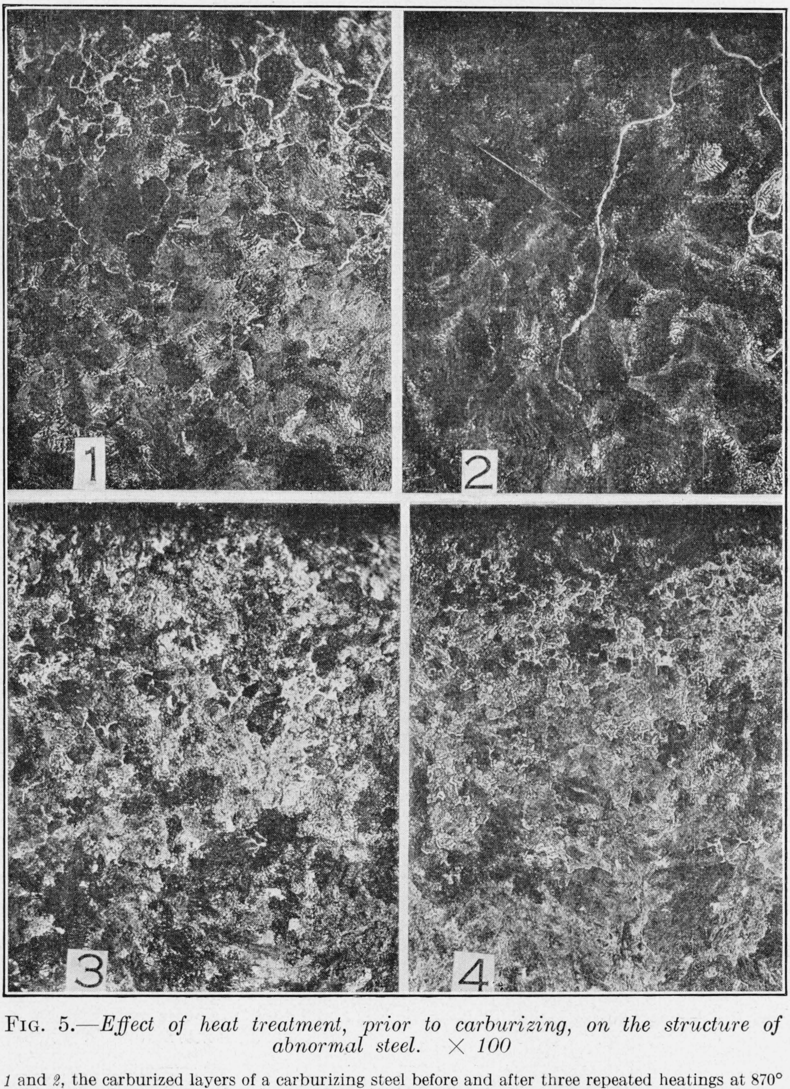

Fig. 5.—*Effect of heat treatment, prior to carburizing, on the structure of abnormal steel.* × *100*

1 and *2*, the carburized layers of a carburizing steel before and after three repeated heatings at 870° C. for 20 minutes and cooling in air. It can be seen that the heat treatment produced a change toward a more normal carburized structure; *3* and *4*, the carburized layers of an abnormal steel before and after three repeated heatings at 870° C. for 20 minutes and cooling in air. The heat treatments had no effect on the carburized structure had the same normal structure as the original bar. A three-sixteenth-inch thick flat bar cold-rolled from a 1-inch round had the same abnormal structure as the original bar. In neither case did annealing the cold-rolled bar prior to carburizing have any effect on the resulting structure. Merten[7] has stated that a strained condition in steel affects the structure after carburizing and illustrated his point by specimens bent into a U shape, the carburized layers of which were deeper on the outer side of the bend (stressed in tension) than on the inner side (stressed in compression). Tests at the bureau confirmed the difference in thickness of the carburized layers in similar specimens. However, when the carburizing was done on the specimens remaining after cutting away the sides of the U and leaving only the bent portion, no difference in thickness of carburized layer between the outer and inner side of the bend was obtained. This indicated that the shallower carburized layer inside the U was due to a lower concentration of carburizing material in the recess at the bend; that is, the result was due to the shape of the specimen rather than to the compressive strains. The conclusion appears to be warranted that cold-work or strain has practically no effect on normality.

(b) HEAT TREATMENT

In regard to the effect of heat treatment, the Bureau of Mines,[8] which has also been studying the problem of normal and abnormal steel, has reported that in some instances heating an apparently abnormal steel to about 870° C. (1,600° F.) for 20 minutes and cooling in air resulted in a more normal structure on subsequent carburizing. It was also stated that some steels which were not transformed to a more normal structure by a single heating and cooling approached nearer to a normal structure after repeated heating and cooling. These results were confirmed in a general way by tests at the Bureau of Standards. The more pronouncedly abnormal steels, however, were scarcely affected by as many as 10 repeated treatments. Figure 5 shows the structure of a sample of steel which was changed to a more normal structure by three repeated treatments, and of another sample not affected by these treatments.

In the matter of classification, the fact that one steel may be made normal or more nearly so by heat treatment, while another may not be affected, might, perhaps, be taken into account. The process by which the transformation is brought about is of some theoretical interest, since it should throw some light on the cause of abnormality. As a useful means, however, of changing abnormal steel to normal the heat-treatment method appears to be impracticable, since not all steels are affected and most steels would require repeated treatments.

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[7] W. J. Merten, Discussion of papers on normal and abnormal steel, Trans. Am. Soc. Steel Treat., **12**, p. 416; 1927.

[8] R. B. Norton, Thesis on Abnormal Steel, 1926, Carnegie Institute of Technology.

(c) ANNEALING IN HYDROGEN

A series of tests has recently been described[9] in which normal and abnormal steels were heated or melted in various atmospheres. The statement was made that abnormal steel when melted in vacuo persisted in remaining abnormal in its behavior. At the Bureau of Standards a change in the structure of some steels, from abnormal to normal, has been produced by heating in hydrogen. This effect was confined, however, to the zones decarburized by the hydrogen. Figure 6 shows a cross section of a specimen of abnormal carburizing steel after being heated at 830° C. for 24 hours in an atmosphere of hydrogen. The outer zone has the appearance of having been completely decarburized. The coarse, columnar crystal formation in the carburized zone, similar to that in a casting, is noteworthy. Apparently the crystals of ferrite originated at the surfaces and then grew inward perpendicularly from the surfaces as decarburization proceeded. Austin[10] has reported observations of this effect of hydrogen.

After having been heated in hydrogen, the specimens were sectioned and then carburized, so that a carburized layer was obtained both at the interior, which had not been affected by the hydrogen treatment, and at the surface decarburized by the hydrogen. As can be seen in Figure 7, the interiors of the specimens remained abnormal, but in the portion decarburized by hydrogen the structures had been changed to normal, except in the last specimen, which was originally the most pronouncedly abnormal one. In open-hearth iron, which is generally very abnormal, no change to a more normal structure was produced by heating in hydrogen at 830° C. for 72 hours. The first presumption might be that this effect of hydrogen in converting an abnormal structure to normal is due to the reduction by the hydrogen of oxides present in the steel. Other factors probably enter in, however, since hydrogen is not very active in reducing aluminum oxide. This was present in the first specimen in Figure 7 and apparently was a cause of its being abnormal. The larger-grain size and thus more normal appearance of the carburized structure, after heating in hydrogen, may, to some extent, be a reflection of the coarse, columnar structure formed in the surface layer decarburized by the hydrogen.

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[9] O. E. Harder, L. J. Weber, T. E. Jerabek, "Studies on normal and abnormal carburizing steels," Trans. Am. Soc. for Steel Treat., **13**, p. 961; 1928.

[10] C. R. Austin, "Hydrogen decarburization of carbon steels, with considerations on related phenomena," J; Iron and Steel Inst., **105**, p. 93, 1922.

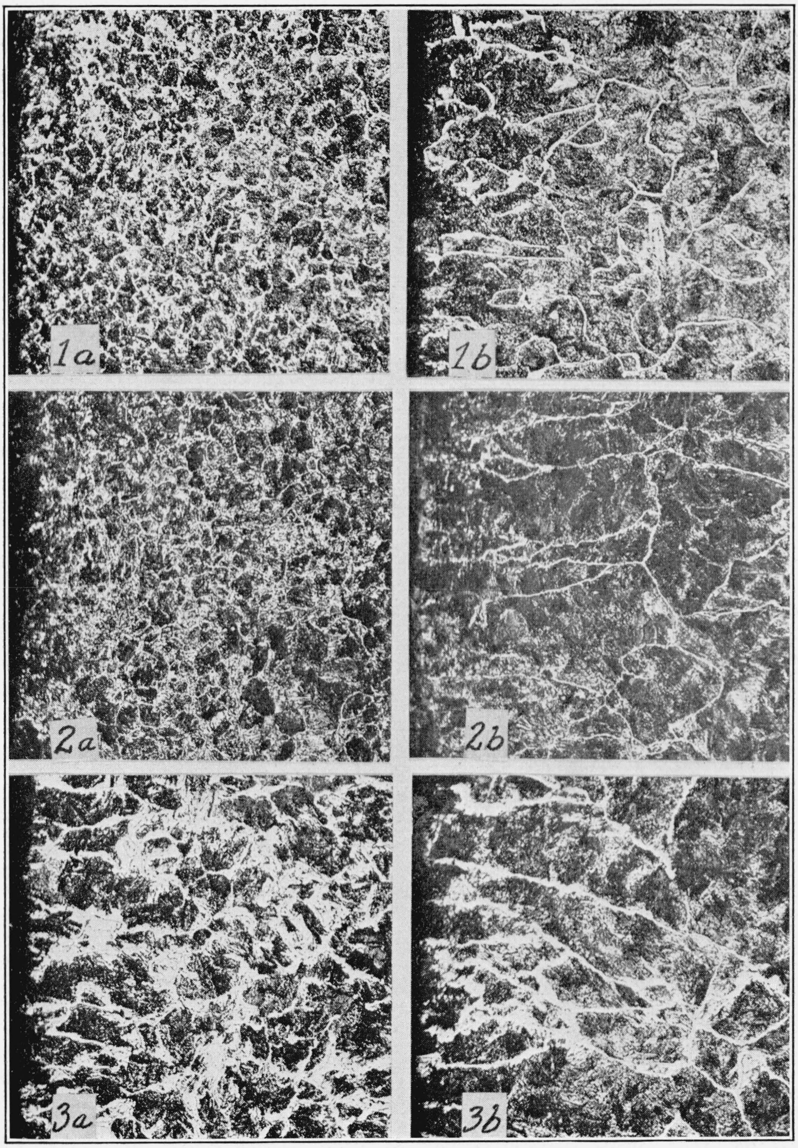

FIG. 7.—*Changes in structure produced in abnormal steel by heating in hydrogen at 830° C. for 24 hours.* × *100*

1a, 2a, 3a, carburized layer in interior not decarburized by hydrogen; the steel remained abnormal; *1b, 2b, 3b,* carburized layer at surface decarburized by hydrogen; the steel appears more normal in structure. Specimens 1 and 3 were of carburizing steel, specimen 2 of tool steel. Specimen 3 did not become so normal as the other two

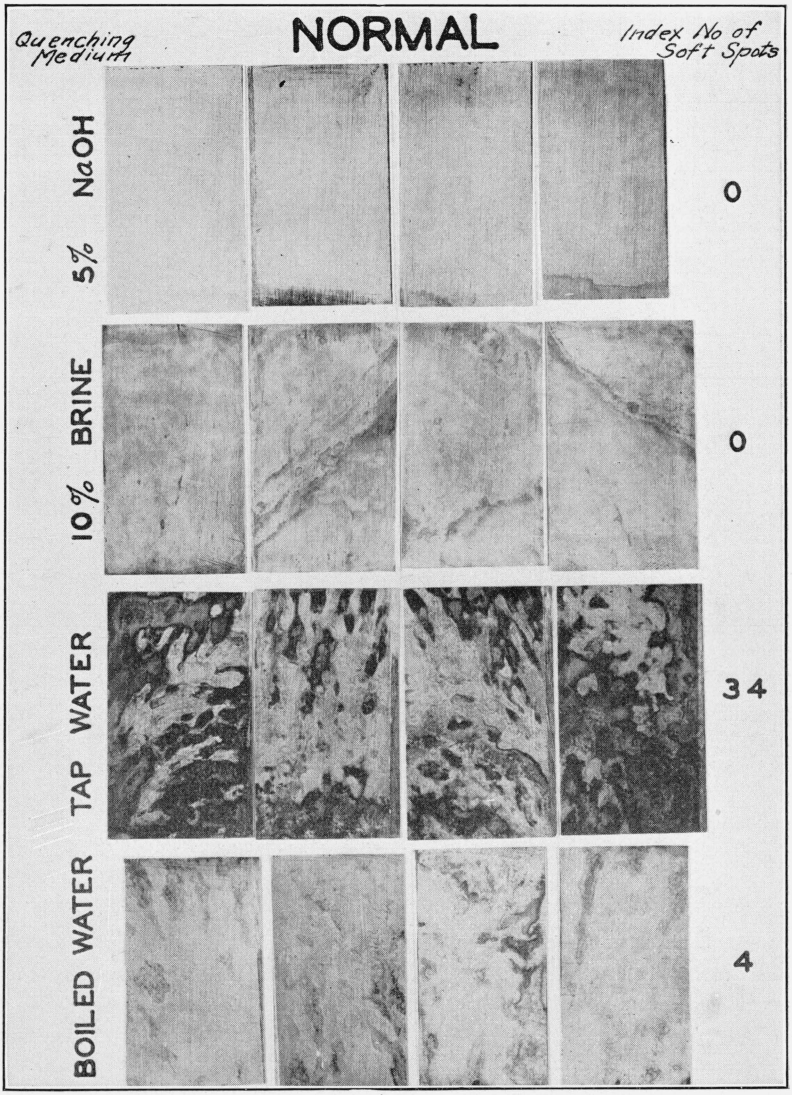

FIG. 8.—*Appearance of the four side faces of blocks of normal steel heated in a cyanide salt bath and quenched in the coolants indicated. About* × ½

The relation is shown between the discolorations on the surfaces and the number of soft spots

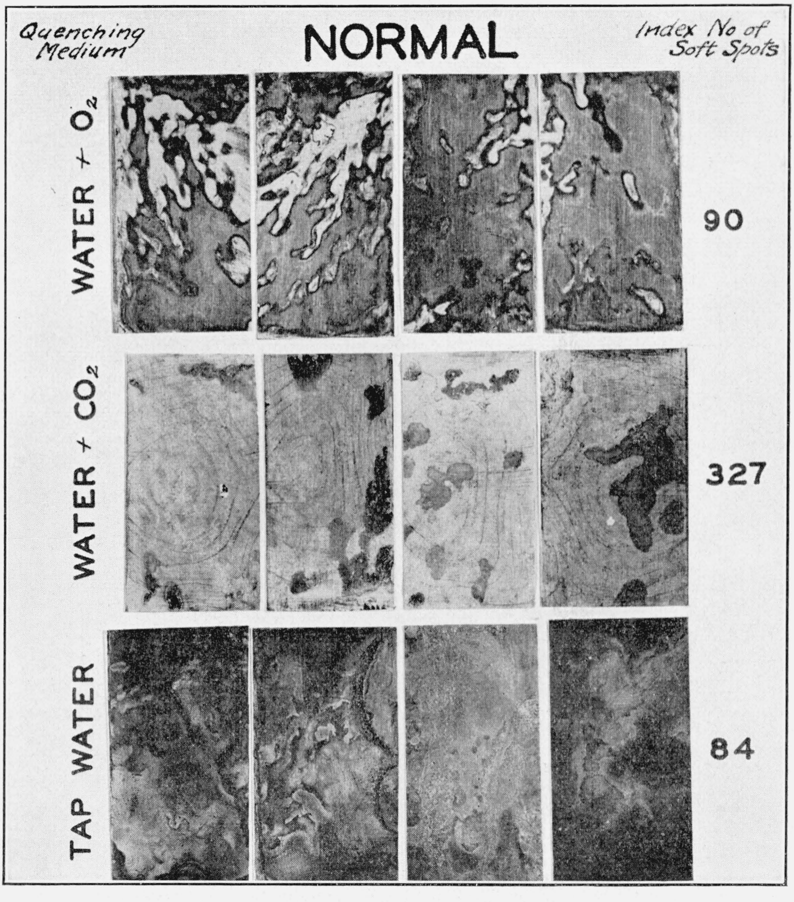

FIG. 8.—(*Continued*)

The last specimen was heated in an electric furnace with access to air, instead of in a cyanide salt bath, before quenching in the tap water. Note the scale on the surfaces

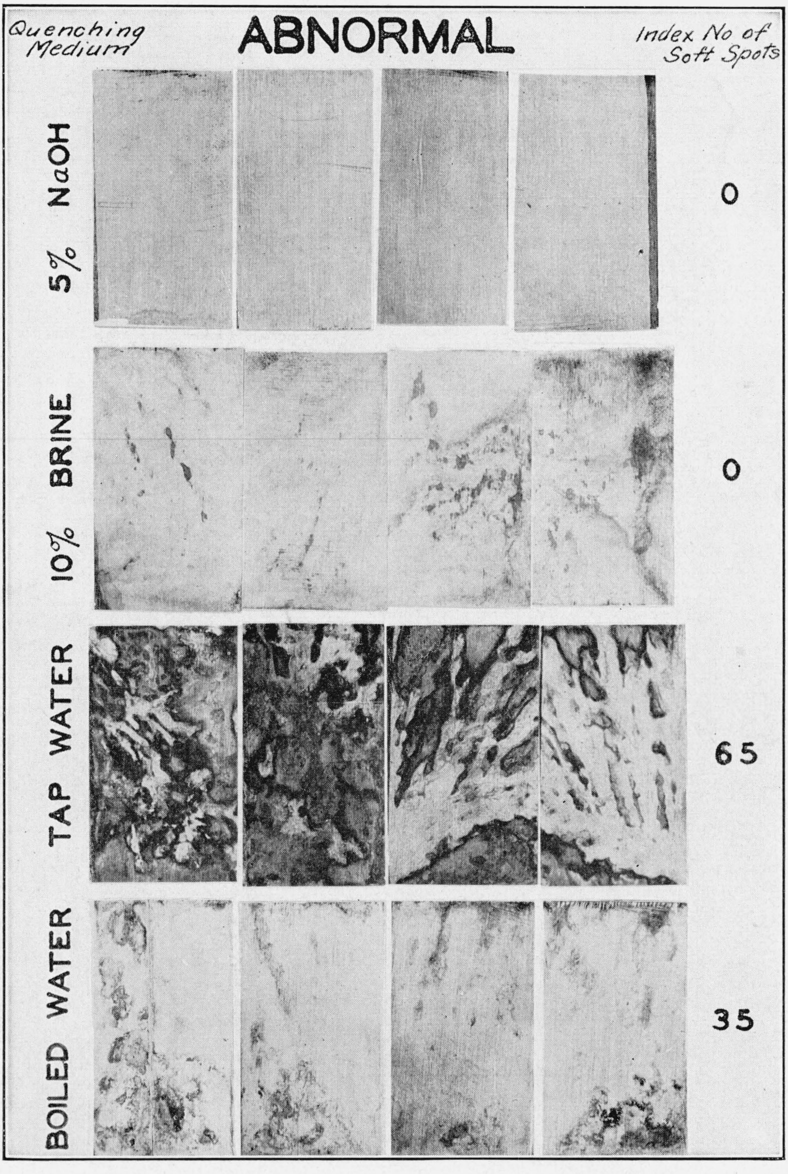

FIG. 9.—*Appearance of the four side faces of blocks of abnormal steel heated as in Figure 8 and quenched as shown. About* × ½

The specimens of Figure 8 were paired with those of Figure 9, during heating and quenching

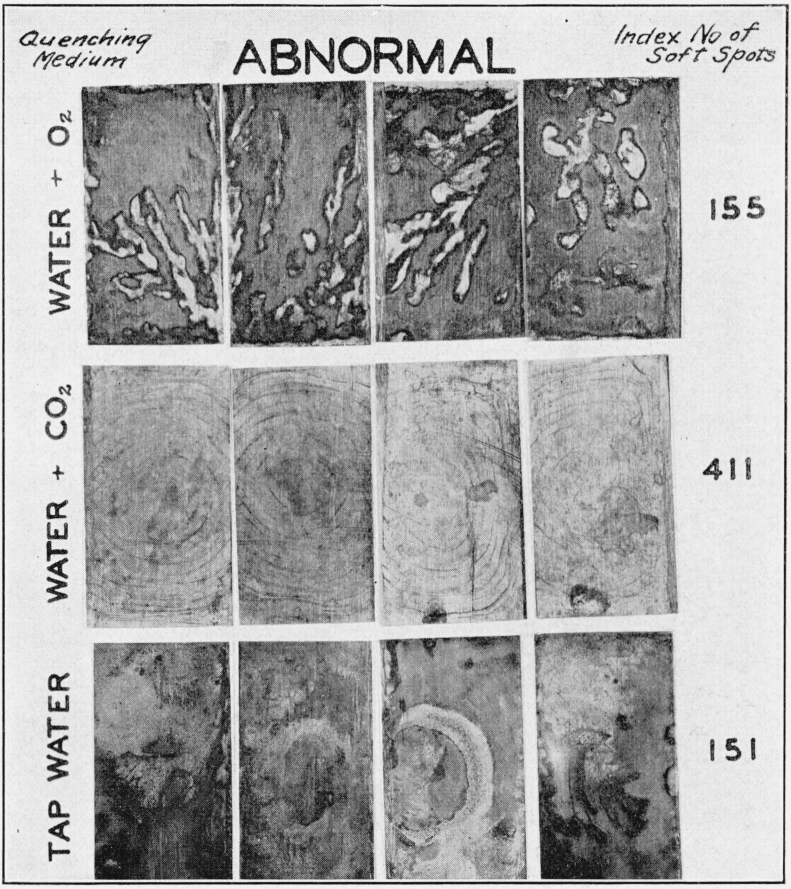

FIG. 9.—(*Continued*)

The last specimen was heated in an electric furnace with access to air, instead of in a cyanide salt bath before quenching in tap water. Note the scale on the surface

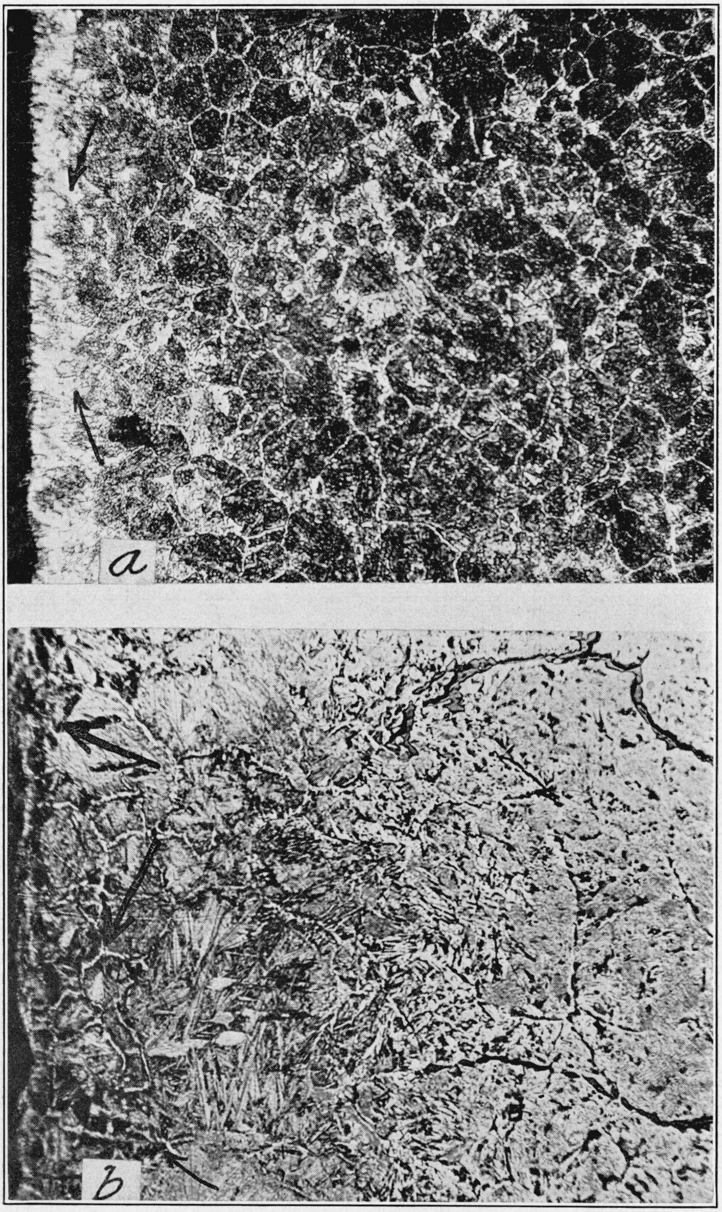

FIG. 10.—*Structure of "file soft" and pseudo "file soft" carburized surfaces.* × 250

a, carburized layer of 5 per cent nickel steel showing ferrite at surface formed during cooling in the carburizing pot; *b*, carburized layer of normal S. A. E. 1020 steel, heated for two hours in a cyanide bath at 775° C. showing formation of coarsely martensitic layer at surface during prolonged heating in cyanide bath. × 250. Etchant, hot alkaline sodium picrate solution. Note the cracks and hard brittle constituent, probably an iron nitride, at the extreme edge

III. QUENCHING TESTS AND HARDNESS MEASUREMENTS FOR SOFT SPOTS

In the operations of casehardening there are so many possible irregularities which may cause soft spots that the first reaction to the claim that soft spots are to be attributed to the steel was to seek the cause in some shortcoming in the carburizing or quenching operations or, as Hatfield[11] stated it, "indifferent hardening." Much argument about normal and abnormal steel turns largely about this point, and it was the first aim of the present study to show whether abnormal steel is more prone to give soft spots than normal steel. The method used was to quench carburized samples of normal and abnormal steel, of the same size, similarly treated in pairs, and to make Rockwell hardness surveys of the surfaces.

1. EFFECT OF DISSOLVED GAS IN WATER USED FOR QUENCHING

An observation as to the effect of dissolved gas in the water used for quenching should first be described. This behavior of dissolved gas applies to the quenching of steel in general, and not alone to the problem of abnormal steel. In an early series of tests the specimens were heated, prior to quenching, in the usual type of electric muffle furnace, which, of course, is not air-tight. More soft spots appeared in the abnormal than in the normal samples, but the objection[12] was raised to these results that with access to air there is considerable scaling and that the scale on the surface may have been primarily responsible for the soft spots. Heating in a salt bath to which cyanide had been added to obviate scaling eliminated the soft spots on *brine quenching*, but, in repeated tests, soft spots were invariably formed on *water quenching* from the cyanide salt bath.

The soft spots were found to be associated with blue and brown discolorations of the surface. The discolorations appeared to be formed while the specimens were in the water and were finally traced to the presence of dissolved air in the tap water used. When the water was boiled to expel the dissolved gas, the discolorations became much less marked, and there was a decrease in the number of soft spots. When oxygen was bubbled through the boiled water, the discolored areas reappeared, accompanied by an increase in the number of soft spots on specimens quenched in such water. When carbon dioxide gas, which is extremely soluble in water, was bubbled through the water (of course, previous to and not simultaneously with the quenching), no marked discolored areas appeared, since

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[11] W. H. Hatfield, Discussion of E. W. Ehn: "Influence of dissolved oxide on the carburizing and hardening qualities of steel," J. Iron & Steel Inst., **105**, p. 198, 1922.

[12] J. W. Napier, Carnegie Steel Co., personal communication.

the carbon dioxide did not oxidize the steel, but practically the entire surfaces of the specimens were soft.

On quenching in 10 per cent brine, in saturated brine, and in a 5 per cent sodium hydroxide solution, the surfaces were not discolored, and there were no soft spots in either the normal or abnormal specimens. This is in agreement with the work of Merten.[13]

Figures 8 and 9 show photographs, about half natural size, of the appearance of the four side surfaces of representative blocks (1½ by 1½ by 2 inches) after these tests. Normal and abnormal blocks, after carburization, were heated in pairs (775° C. (1,425° F.) for 30 minutes) in a cyanide salt bath and quenched in the media indicated. The "index number of soft spots" given for each specimen was obtained empirically in the following manner: 24 Rockwell readings, C scale, spaced equidistantly from each other were taken in three rows on each side of the block, a total of 96 readings for each specimen. In the hard martensitic areas the average reading was about 65. Readings below 60 were taken as an indication of softness. The following weights were given to the "soft readings": From 60 to 55, 1; from 55 to 50, 2; from 50 to 45, 3; below 45, 4. The "index number of soft spots" for any specimen is the sum of the weights of the soft readings out of the 96 readings on the specimen. As can be seen in the photographs, the specimens quenched in sodium hydroxide or brine were not discolored and had no soft spots; those quenched in tap water were discolored and had a good many soft spots; those quenched in boiled water were less discolored and had fewer soft spots; those quenched in boiled water through which oxygen had been bubbled were discolored and had a good many soft spots; those quenched in boiled water through which carbon dioxide had been bubbled were not very much discolored but had a profusion of soft spots. It should be noted that, whenever soft spots were formed, more appeared in the abnormal than in the normal sample, although no difference in the extent of the discoloration was detectable.

The most plausible explanation for the effect of dissolved gas in quenching water is that, when the hot specimen is immersed in the water, the dissolved gas comes out of solution and clings to the specimen, retarding heat abstraction from the interior of the steel because of the low heat conductivity of the gas. In the specimens quenched in tap water and water containing oxygen the soft spots were located in the discolored areas. The discolorations themselves, however, should not be considered as a direct cause of the soft spots; they are simply evidence of the presence of an oxidizing gas. The effect in producing soft spots was similar when an inert gas-like nitrogen, which produced no discolorations, was dissolved in the water.

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[13] W. J. Merten, "Fused salt baths for the prevention of soft spots in quenched high-carbon and carburized steels," Trans. Am. Soc. Steel Treat., 7, p. 23, 1925. W. J. Merten, "Irregular carburization of iron and iron alloys—the cause and prevention," Trans. Am. Soc. Steel Treat., 9, p. 907; 1926.

As has been stated, the extent of the discolored areas in the photographs of the surfaces of the quenched specimens is alike in the normal and abnormal samples, but the latter have the larger "index numbers of soft spots." Where gas adhered to an abnormal sample and gave a discolored area, a soft spot was usually formed, the cooling at the spot evidently being slower than the critical cooling rate necessary for the formation of martensite for that type of steel. Normal steel appears to have a lower critical rate, since the slower cooling in the discolored areas was often fast enough to give martensite; fewer discolored areas were soft in the normal steel than in the abnormal steel.

Incidentally, it may be pointed out that quenching tests and hardness surveys so made afford a delicate means of revealing any difference in the critical cooling rate between two steels, it being possible by adjusting the size of specimen and the kind and temperature of the quenching medium to get into the critical range. Slight differences in the critical rate will then throw the balance of the reaction to one side or the other, giving either the Ar′ transformation to troostite, or the Ar″ transformation to martensite, with their measurable differences in hardness. In the same way slight differences in cooling rates of quenching media may be observed, as in the effect of the dissolved air in water, described above. Benedicks,[14] while making direct measurements of the cooling power of water, thought he noticed an effect of dissolved air but finally decided that his measurements showed no perceptible difference between aerated water and distilled water. This result may be called in question, however, since in the same work he also concludes that brine does not surpass water in cooling power, a conclusion which later investigators have disproved.[15]

Water generally contains about 2 per cent by volume of dissolved air (about 1.3 per cent nitrogen and about 0.7 per cent oxygen), depending somewhat on the seasonal changes in temperature. The amount of dissolved air does not differ very greatly for water of different localities. The carbon dioxide content, however, varies considerably, from about 0.2 per cent in mountain-river water to as high as 5 per cent in deep limestone-well water. A large proportion of the dissolved carbon dioxide in deep well water is combined with calcium carbonate as bicarbonate, but the carbon dioxide is readily evolved upon heating, whence the name temporary hard water. In a few rough trial quenching tests made with the hard water of Canton, Ohio, to see if this water, which is reputed to have a high carbon

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[14] C. Benedicks, "Cooling power of liquids, quenching velocities, etc.," J. Iron & Steel Inst., 77, p. 153, 1908.

[15] N. B. Pilling and T. D. Lynch, "Cooling properties of technical quenching media," Trans. Am. Inst. Min. & Met. Engrs., 62, p. 2347; 1920. H. J. French and O. Z. Klopsch, "Quenching diagrams for carbon steels in relation to some quenching media for heat treatment," Trans. Am. Soc. Steel Treat., 6, p. 251; 1924.

dioxide content, would produce more soft spots than the Washington water with a low carbon dioxide content, no differences were found. It is well, however, while considering the effect of air dissolved in quenching water, to mention also the possible effect of other gases like carbon dioxide, which may be present in relatively large amounts in the ground water of some localities.

2. THE STRUCTURE OF SOFT SPOTS

Mainly, by way of illustration, it is of interest to examine the structure of soft spots in normal and abnormal steel. Soft spots formed during quenching may readily be recognized by their troostitic structure and thus differentiated from soft spots caused by failure of carbon to penetrate scale on the surface, and from soft areas due to decarburization during cooling in the carburizing pots, which may sometimes occur. The arrow in Figure 10 (*a*) points to a thin ferrite layer at the extreme edge of a carburized specimen of 5 per cent nickel steel, the ferrite layer evidently having formed during cooling in the carburizing pot. The thin surface layer of ferrite was, of course, "file soft" after hardening. Although it may seem paradoxical, apparent file softness of a steel surface may also be produced by prolonged heating in cyanide. During heating in cyanide prior to quenching a nitrogenized layer may be formed at the surface, and, if the heating is prolonged, this layer becomes permeated with cracks. In Figure 10 (*b*), which depicts the structure at the surface of a carburized specimen heated for two hours in a cyanide bath, the outer zone shows a coarse martensitic structure, produced apparently by the penetration of nitrogen. At the extreme outer edge the arrows indicate cracks and fissures and a hard, brittle constituent, probably an iron nitride. The extreme outer layer readily crumbled upon cutting with a file and thus gave the impression of file softness. Such surface embrittlement was not noticed with moderate periods (of about one-half hour) of heating in the cyanide bath.

The appearance of soft spots formed during quenching is illustrated by Figure 11, which shows cross sections of normal and abnormal steel blocks quenched from a cyanide salt bath into tap water, deeply etched with hot 1:1 hydrochloric acid. The difference in grain size between the normal and abnormal steel is noticeable. After deep etching, the troostitic areas appear lighter in color than the martensitic areas, the effect being directly opposite to that produced by etching for microscopic examination. It can be seen that the troostitic areas in the abnormal steel were greater in extent than in the normal steel. Figure 12 shows micrographs of the soft spots. In the abnormal steel the soft spots were more completely troostitic; in the normal steel there was generally some martensite present together with the troostite, especially in the transition zone between the case and core. The difference in the form of the cementite between the normal and abnormal steel is evident. The white layer at the extreme edge in both micrographs is due to nitride penetration during heating in the cyanide bath prior to quenching.

3. NUMBER OF SOFT SPOTS

(a) EXTREMES OF NORMALITY AND ABNORMALITY

We may now turn to the results of the Rockwell hardness surveys of pairs of carburazed and quenched specimens of normal and abnormal steel, as shown in Table 2. The specimens used were blocks similar to the ones shown in Figures 8 and 9 and had structures corresponding to the extremes of the normal and abnormal structures illustrated in Figure 1. The method of obtaining the "index number of soft spots" has been described above (p. 432). The specimens were heated for 30 minutes at 775° C. (1,425° F.) before quenching. The chemical compositions of the normal and abnormal specimens were practically identical (carbon 0.14 per cent, manganese 0.35 per cent).

TABLE 2.—*Relative tendency of normal and abnormal steel to the formation of surface soft spots upon hardening after carburizing*

[The specimens were heated [1] in pairs and quenched in the designated media]

Pair No.	Heated in—	Quenched		Index number [2] of soft spots	
		In—	At—	Normal	Abnormal
			°C.		
1	Air [3]	Tap water	16	84	200
2	do	do	11	9	11
3	do	do	11	21	86
4	do	do	16	12	90
5	do	do	17	1	21
6	do	do	17	6	45
7	do	do	17	0	96
8	Gas [4]	do	17	135	276
9	do	do	17	87	118
10	do	do	11	1	22
11	do	do	10	17	35
12	Chloride salt bath [5]	do	8	122	193
13	do	do	12	11	131
14	do	do	13	48	168
15	Cyanide salt bath [6]	do	12	43	112
16	do	do	12	52	102
17	do	do	12	4	17
18	do	do	10	1	1
19	do	do	15	0	43
20	do	do	16	19	37
21	do	do	16	17	48
22	do	do	15	24	57
23	do	do	14	17	49
24	do	do	14	26	64
25	do	do	9	28	50

[1] At 775° C. for 30 minutes.

[2] Meaning of index numbers given on p. 432.

[3] Heated in an ordinary electric muffle furnace, which allows access to a limited amount of air.

[4] Heated in an electric muffle furnace filled with illuminating gas.

[5] 78 per cent $BaCl_2$, 22 per cent NaCl salt bath.

[6] A mixture of sodium carbonate and sodium chloride with about 25 per cent sodium cyanide was used. As the cyanide content became exhausted, new additions of sodium cyanide were made to the bath.

TABLE 2.—*Relative tendency of normal and abnormal steel to the formation of surface soft spots upon hardening after carburizing*—Continued

No.	Heated in—	Quenched		Index number [2] of soft spots	
		In—	At—	Normal	Abnormal
			°C.		
26	Cyanide salt bath	Tap water	13	34	65
27	do	do	8	49	173
28	do	do	8	52	149
29	do	do	19	0	10
30	do	do	28	1	153
31	do	do	20	2	14
32	do	do	28	3	20
33	Air	Boiled water	21	66	158
34	do	do	23	14	126
35	do	do	10	12	67
36	do	do	10	12	2
37	Gas	do	11	1	27
38	do	do	12	2	68
39	do	do	24	126	321
40	do	do	25	217	321
41	Chloride salt bath	do	12	14	25
42	Cyanide salt bath	do	8	0	5
43	do	do	9	4	35
44	do	do	3	0	21
45	do	do	3	1	5
46	do	Boiled water plus oxygen	15	90	155
47	do	do	11	36	128
48	do	Boiled water plus hydrogen	8	32	55
49	do	do	8	27	61
50	do	Boiled water plus nitrogen	14	41	165
51	do	do	14	107	144
52	do	do	12	38	146
53	do	do	12	57	184
54	do	Boiled water plus carbon dioxide	16	390	428
55	do	do	17	327	411
56	Air	15 per cent brine [7]	16	0	2
57	do	do	20	0	0
58	Gas	10 per cent brine	15	0	0
59	do	15 per cent brine	22	0	2
60	do	do	26	0	4
61	Chloride salt bath	10 per cent brine	16	0	0
62	do	do	16	0	0
63	do	do	18	0	0
64	do	do	12	0	0
65	do	do	13	0	0
66	do	do	17	0	0
67	do	do	19	0	0
68	do	Saturated brine	18	0	0
69	do	do	18	0	23
70	Cyanide salt bath	10 per cent brine	13	0	0
71	do	do	14	0	0
72	do	do	11	0	0
73	do	do	13	0	0
74	do	do	17	0	0
75	do	Saturated brine	7	0	0
76	do	do	10	0	0
77	do	Saturated brine plus carbon dioxide	10	58	155
78	do	do	10	112	278
79	do	10 per cent brine plus carbon dioxide	8	167	314
80	do	do	8	145	274
81	Air	5 per cent sodium hydroxide	24	0	0
82	do	do	22	0	0
83	Gas	do	23	0	0
84	do	do	20	0	0
85	do	do	21	0	0
86	do	do	22	0	4
87	Chloride salt bath	do	12	0	0
88	Cyanide salt bath	do	8	0	0

[7] Sodium chloride brine.

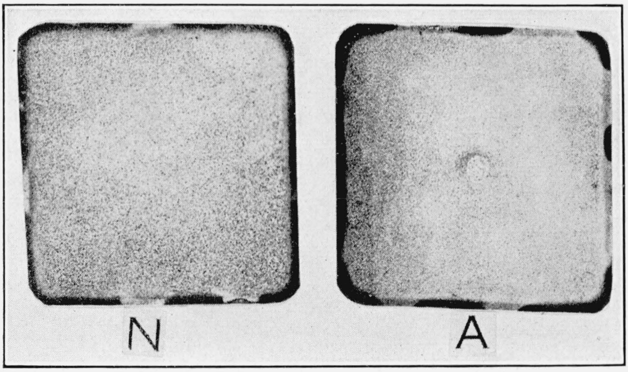

FIG. 11.—*Cross sections of normal and abnormal steel blocks heated together in a cyanide bath and quenched simultaneously in tap water; deeply etched with hot 1 : 1 hydrochloric acid.* × 1

In the carburized layers, the dark portions are hard, and the light portions are soft spots. It can be seen that there are larger soft areas in the abnormal specimen

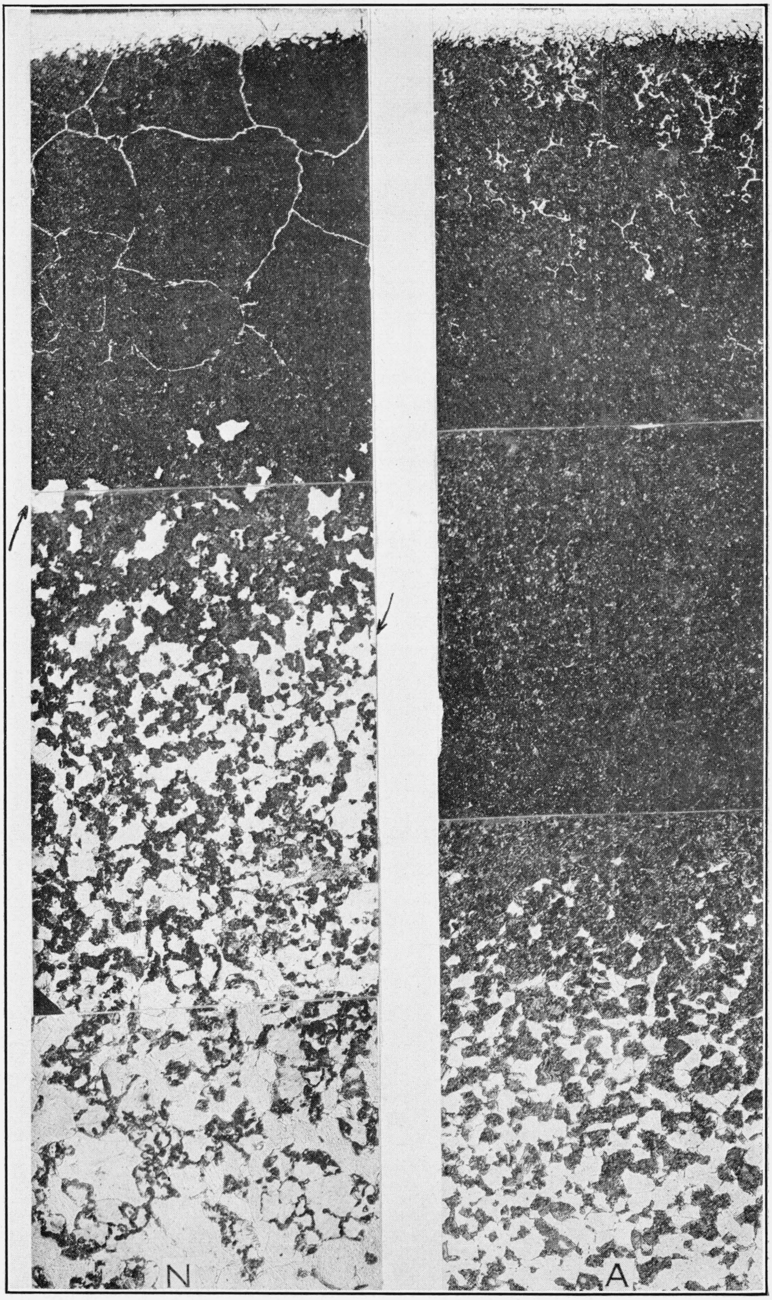

FIG. 12.—*Structure of soft spots in normal and abnormal casehardened steel.* × *100*

In the carburized layer of the abnormal steel the soft spot is completely troostitic, whereas in the normal steel there is some martensite present, together with the troostite. The martensite is indicated by arrows. The white border at the extreme outer surface in both specimens is due to nitrogen penetration during the heating in the cyanide bath prior to quenching

The data in Table 2 show a consistent difference in the number of soft spots between normal and abnormal steel and clearly indicate that abnormal steel is more prone to give soft spots. The data of Table 2 also show that with the use of a drastic quenching medium, such as sodium chloride brine or sodium hydroxide solution, the formation of soft spots can be completely prevented in both normal and abnormal steel. A word may be said as to the effect of the heating medium. Although in some of the tests more soft spots were obtained upon heating in an air or gas atmosphere, where scaling was possible, than upon heating in a cyanide salt bath, the data in Table 2 indicate that, as regards the elimination of soft spots, the type of quenching medium used is of much greater importance than the manner of heating.

The advisability of changing from water quenching to a more drastic medium like brine, water-pressure spray, or sodium hydroxide solution, deserves careful consideration. With most casehardened articles there is small danger from cracking. The question is whether drastic quenching will increase distortion or warpage. The view might be taken that warpage is, perhaps, more a result of uneven-temperature gradients than steep gradients, and that there would thus be no increase in troubles from warpage if the more drastic methods of quenching were adopted to avoid soft spots. However, it would require considerable study to ascertain this point. To throw some possible light on it, a few trial quenching tests were made of carburized hollow cylinders, 2½ inches long, 1½ inches outside diameter, and ¼-inch wall thickness. Very precise measurements [16] were made, with a Prestwich gauge, of the lengths and diameters of the cylinders before and after quenching in oil, water, brine, and sodium hydroxide solution. Two types of steel were used, normal S. A. E. 1020 steel (C, 0.22 per cent; Mn, 0.53 per cent; P, 0.018 per cent; S, 0.048 per cent; Si, 0.02 per cent), and the special manganese carburizing steel M (C, 0.19 per cent; Mn, 1.04 per cent; P, 0.060 per cent; S, 0.062 per cent; Si, 0.13 per cent). Three elements of length at angles of 120° were measured, and three measurements were made on each specimen of the diameters, at the two ends and middle of the cylinder along each of the three elements, before and after quenching. A survey was also made of the number of soft spots in the quenched specimens. The specimens were then tempered for one hour at 200° C. (392° F.) and similar measurements made. The arithmetical sums of the maximum positive and negative deviations from the mean change in dimension from the original size of the carburized cylinders, after quenching and after tempering, is given in Table 3.

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[16] Ralph F. Staubley, jr., laboratory aid, Bureau of Standards.

TABLE 3.—*Dimensional changes produced in carburized hollow cylinders by quenching in various media*

[Arithmetical sums of maximum positive and negative deviations from mean change in dimension, in thousandths of an inch]

Quenching medium	Special manganese carburizing steel [1]					S. A. E. 1020 steel [1]				
	Specimen No.	Length		Diameter		Specimen No.	Length		Diameter	
		Quenched	Tempered	Quenched	Tempered		Quenched	Tempered	Quenched	Tempered
Oil	A-1	0.22	0.18	0.38	0.66	B-1	0.45	0.57	2.37	2.57
	A-2	.04	.14	.56	.96	B-2	.13	.21	1.17	1.19
	A-3	.37	.55	.57	.65	B-3	.37	.13	2.63	2.43
		(No soft spots)					(Very many soft spots)			
Water	A-4	.42	.43	1.55	2.00	B-4	.57	.50	2.95	2.70
	A-5	.18	.09	1.47	1.52	B-5	.27	.31	1.18	1.63
	A-6	.47	.34	1.38	1.38	B-6	.26	.23	1.43	1.38
		(No soft spots)					(Soft spots only in specimen B-4)			
5 per cent NaOH	A-7	.57	.29	3.25	3.25	B-7	1.20	1.20	2.40	1.90
	A-8	.73	1.05	1.74	1.84	B-8	.78	.18	2.86	2.43
	A-9	.65	.75	1.75	2.65	B-9	1.03	1.28	2.75	3.23
		(No soft spots)					(No soft spots)			
10 per cent brine	A-10	.66	.86	2.88	2.70	B-10	1.04	2.07	2.25	2.15
	A-11	.77	.80	1.92	1.60	B-11	.27	.38	1.17	2.48
	A-12	1.77	1.87	1.97	2.69	B-12	1.44	.59	2.43	2.48
		(No soft spots)					(No soft spots)			

[1] See p. 437 for chemical composition.

It seems justifiable to take the deviations from the mean change in dimensions in Table 3 as an indication of the amount of warpage. In the special manganese carburizing steel, which, it will be noted, hardened without soft spots even on oil quenching, the least "warpage" occurred on oil quenching. Upon water quenching there was more "warpage," and there was still more with the more drastic quenching media—brine and sodium hydroxide. In the plain carbon steel, which, it will be noted, did not harden in oil, there was about the same amount of warpage on oil quenching as on quenching in the more drastic media. The large amount "warpage" of the plain carbon steel upon oil quenching may have been due to the nonuniform hardening. In accord with this assumption, specimen B-4, the water-quenched plain carbon steel which had some soft spots, whereas its two companion specimens did not, showed the most "warpage" in its group. The data at hand are much too meager for definite conclusions, but they seem to indicate that the least warpage occurs with the use of the mildest quenching medium that will still give uniform hardening. For sizes in which the special manganese steel or similar steel would harden uniformly on oil quenching, whereas plain carbon steel would not, this fact would appear to make it possible to obtain less warpage with such alloy steels than with plain carbon steel.

The more drastic quenching media, such as brine, are being very generally used, however, especially for large casehardened articles.

High-pressure water-spray quenching has also found favor. An advantage of quenching in brine and especially in sodium hydroxide is the very clean bright surface of the work obtained.

(b) INTERMEDIATE GRADATIONS

(1) FINE-GRAINED NORMAL STEEL.—As has been stated, the difference in the number of soft spots between normal and abnormal steel shown in Table 2 was obtained with steels showing the extremes of the normal and abnormal structure. No definite data are available for the intermediate gradations. Among these, interest centers mainly on the fine-grained steels showing no coalescence of the cementite. To determine the tendency to form soft spots of such steels would necessitate making quenching tests and hardness surveys of specimens of the same composition, showing a wide variation in grain size and no coalescence of the cementite. Such specimens could not be procured, however, the reason being that in the plain carbon steels small-grain size was always accompanied by more or less coalescence of the cementite. In some alloy steels, on the other hand, it was possible to get fine-grain size without, or with only very slight, coalescence of the cementite, but these alloy steels were always fine grained, and no coarse-grained material of the same composition could be obtained for comparison. Gat [17] has presented data intended to show that in a steel with no coalescence of the cementite fine-grain size does not indicate any tendency to form soft spots. However, he used only the fine-grained alloy steels, without making any comparison tests with similar coarse-grained steels, and it is most probable that the uniform hardness he obtained was due to the deep hardening properties conferred by the alloying elements. Whether or not, therefore, fine-grained size of itself, and when not accompanied by coalescence of the cementite, should be regarded as a feature of abnormality and as an indication that a faster quenching rate is necessary for uniform hardening than with coarse-grained steels of the same composition remains unsettled. However, the question here involved is academic rather than practical, since the fine-grained alloy steels do not appear to be prone to form soft spots in practice. These steels have been classed by some metallurgists as "fine-grained normal" and are regarded as particularly desirable, it being considered that their fine grain allows the so-called "core-refining heat" or "regenerative quench" in the heat treatment after carburizing to be dispensed with.[18]

(2) KILLED AND EFFERVESCENT STEEL.—Another intermediate grade is that of a coarse-grained steel showing somewhat thickened cementite envelopes, with occasional thin ferrite films about the

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[17] See footnote 5, p. 427.

[18] M. T. Lothrop, Casehardening, Iron Age, 120, p. 612; 1927.

cementite. This structure is usually found in effervescent steel, and the conclusion is sometimes drawn that the distinction between normal and abnormal steel reduces itself in the main to one between killed and effervescent steel. This conclusion was not borne out by the quenching tests and hardness surveys shown in Table 4. Coarse-grained effervescent steel with thick cementite envelopes gave only a few more soft spots than normal killed steel. The difference between normal killed steel and normal effervescent steel was negligible, compared to the decided difference between normal and abnormal effervescent steel and between normal and abnormal killed steel.

TABLE 4.—*Relative tendencies of normal and abnormal steel, both killed and effervescent, toward the formation of soft spots upon hardening after carburizing*[1]

[The index number has the same significance as in Table 2]

Group No.	Temperature of water	Index number of soft spots			
		Killed steel [2]		Effervescent steel [2]	
		Normal	Abnormal	Normal	Abnormal
	°C.				
1	8	0	93	33	58
2	12	18	58	8	136
3	18	2	43	23	29
4	19	8	61	9	49
5	21	44	103	12	89
6	23	18	88	17	87
7	30	4	97	31	57
8	19	17	112	10	193
9	19	25	128	17	192
10	23	14	106	16	130
11	25	12	185	11	136
12	27	6	192	13	210
13	31	6	126	60	203

[1] The four specimens on each horizontal line in the table were quenched together and constitute a group. The specimens used were carburized blocks 1½ inches square, 2½ inches long. They were heated at 775° C. for 30 minutes in a cyanide salt bath and quenched in water through which oxygen had previously been bubbled for 10 minutes.

[2] The compositions were: Killed steel—C, 0.14 per cent; Mn, 0.44 per cent. Effervescent steel—C, 0.14 per cent; Mn, 0.42 per cent.

(c) SPECIAL MANGANESE CARBURIZING STEEL

Of considerable practical importance were the quenching tests and hardness surveys of special manganese carburizing steels. The measurements of the depth of carburized layer (Table 1) should also be noted in this connection. These quenching tests gave the interesting result that the special manganese carburizing steels are much less prone to give soft spots than even normal plain carbon steel, as may be seen from Tables 5 and 6.

TABLE 5.—*Relative tendencies of special manganese carburizing steel and plain carbon normal steel toward the formation of soft spots upon hardening after carburizing* [1]

[The index number has the same significance as in Table 2]

Pair No.	Temperature of water	Index number of soft spots	
		Special manganese carburizing steel J [2]	Normal S. A. E. 1020 steel [2]
	°C.		
1	15	0	50
2	15	0	8
3	17	0	19
4	17	0	42
5	18	1	30
6	18	0	12
7	19	0	46
8	19	0	51
9	22	0	18
10	22	0	25
11	22	2	50
12	22	0	78

[1] The size of the specimens used was similar to that described in Table 4; the quenching treatment was also similar.

[2] The compositions were: Special manganese carburizing steel J—C, 0.16 per cent; Mn, 1.36 per cent; P, 0.018 per cent; S, 0.098 per cent; Si, 0.07 per cent. Normal S. A. E. 1020 steel—C, 0.22 per cent; Mn, 0.53 per cent; P, 0.018 per cent; S, 0.098 per cent; Si, 0.07 per cent.

TABLE 6.—*Relative tendencies of special manganese carburizing steels and plain carbon normal and abnormal steels toward the formation of soft spots upon hardening after carburizing* [1]

[The index number has the same significance as in Table 2]

Group number	Temperature of water	Index number of soft spots			
		Special manganese carburizing steel J [2]	Special manganese carburizing steel M [2]	Normal S. A. E. 1020 steel [2]	Abnormal steel
	°C.				
1	24	0	0	17	114
2	27	0	0	15	83
3	29	0	0	29	160
4	31	0	0	25	143
5	32	0	0	4	130

[1] The size of the specimens used was similar to that described in Table 4; the quenching treatment was also similar. Two kinds of special manganese carburizing steel from two different manufacturers were used; one has been designated "J" and the other "M" throughout this paper.

[2] The compositions were: Special manganese carburizing steel J—see Table 5. Special manganese carburizing steel M—C, 0.19; Mn, 1.04; P, 0.060; S, 0.062; Si, 0.13. Normal S. A. E. 1020 steel—see Table 5. Abnormal steel—C, 0.14 per cent; Mn, 0.43 per cent.

As shown in Table 6, under the conditions of quenching used abnormal steel gave a large number of soft spots, normal S. A. E. 1020 steel gave fewer soft spots, but still a considerable number, whereas neither of the special manganese carburizing steels gave any soft spots. Quenching in water through which oxygen had been bubbled is without doubt as favorable toward the formation of soft spots as the quenching procedure in any reasonably careful heat-treating establishment. The conclusion may be drawn, therefore, that in practice complete freedom from soft spots may be obtained by the use of the special manganese carburizing steels. This would also be true, of course, with any other steel containing alloying elements which conferred deep hardening properties equivalent to that of the manganese in the special manganese carburizing steel.

IV. IZOD IMPACT TESTS

As was indicated at the outset, there appears to be no difference in chemical composition, as ordinarily determined, between normal and abnormal steel, nor is it usually considered that there is a difference between them in mechanical properties. However, McKinney[19] has voiced what is probably the general opinion, in stating that if we consider abnormality to be due to the obstruction offered to perfect crystallization and to grain growth, by particles of oxides, we must regard the quality of abnormal steel in respect to mechanical properties as inferior to normal steel, or at least with suspicion, because of the presence of the oxides. On the other hand, because of its finer-grain size, abnormal steel might be presumed to have higher impact strength than normal steel, and this was very strikingly shown to be the fact by a series of impact tests of normal and abnormal carbon steels, and the special manganese carburizing steel. The specimens were tested after various heat treatments. In Table 7 the results given in the last column under "carburizing treatment" are of principal interest. The "carburizing treatment" consisted in heating the specimens for eight hours at 940° C., as for carburizing, no carburizer being used, however. Tests of these specimens therefore, indicated how tough or brittle the cores of these different steels would be after carburizing. The abnormal specimens gave much higher impact resistance after the "carburizing treatment" than the normal specimens. The special manganese carburizing steels also showed high impact resistance after the "carburizing treatment." The above results were confirmed by another series of tests, as shown in the second column of Table 8.

Brittleness of the core induced by the long-continued heating during carburizing may be removed and toughness restored by the "regenerative treatment"; that is, by quenching from the critical range and drawing back. After this treatment, as shown in the last column in Table 8, the impact strength of the normal and abnormal specimens was the same. Nevertheless, from the viewpoint of toughness of the core, the fine-grain size of abnormal steel is an undoubted advantage; for instance, a wider latitude is allowable in the temperature range of heat treatment. It is doubtless of some practical importance that, with abnormal steel, the regenerative treatment may be more safely dispensed with than with normal steel. For these reasons a metallurgist would probably prefer a finer grained steel to the extreme type of normal steel with very large grain. The fine-grained alloy steels commend themselves for the additional reason that, with these, trouble from soft spots is not likely to occur.

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[19] P. E. McKinney, "Discussion of normal and abnormal steels," Tr. Am. Soc. Steel Treat., 12, p. 427, 1927.

That the practical metallurgist has not been slow to realize these advantages of fine-grain size, at least in the alloy carburizing steels, is well brought out in the reference already given.[20]

It was of interest to test the impact resistance of the core of normal and abnormal steel after the quenching for hardening the case. Bars 1½ inches square cross section were given the "carburizing treatment" and quenched from 775° C. into water, as for casehardening. Standard Izod impact specimens, 1 cm by 1 cm in cross section, were then cut from the bars one-eighth inch and one-half inch below the surfaces. The results are shown in Table 9. The much higher impact resistance of the abnormal steel after this treatment was striking. It was an object of the tests to determine whether or not the high manganese content in the special manganese carburizing steels tended to make the core brittle, after the quenching to harden the case. Although the impact resistance of the two special manganese carburizing steels in these tests was much lower than that of the abnormal steel, it was not apparent that the cores of the special manganese carburizing steels were more brittle than the core of the normal steel. It should be noted that no tests were made in this series in which the regenerative treatment was given specimens after the "carburizing treatment" and previous to the quenching.

TABLE 7.—*Impact resistance*[1] *of normal and abnormal steel and special manganese carburizing steel after various heat treatments*

Specimen No.[2]	Heat treatment				
	As received		Normalized—heated 1 hour at 900° C. and air cooled		Carburizing treatment[3]
	Energy absorbed, in foot-pounds				
Normal steel:					
122	74	73	60	58	23
134	78	59	76	67	23
146	77	77	77	79	31
152	80	82	77	71	42
155	23	23	72	71	17
Abnormal steel:					
113	74	76	77	79	74
119	74	77	77	78	69
125	73	72	75	75	69
137	76	77	78	78	74
143	79	81	80	80	59
149	83	79	82	85	69
Special manganese carburizing steel J	62	63	78	77	70

[1] A 120-foot-pound capacity Izod machine was used. The specimens were triple notched, and each value for energy absorbed is the average for the 3 notches.

[2] For the compositions of these specimens, see Table 1.

[3] By "carburizing treatment" is meant heating for 8 hours at 940° C., and cooling in the furnace as in carburizing (no carburizer being used, however), after which the specimens were machined so that, if any oxidation occurred during the heating, the oxidized surfaces were removed.

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[20] See footnote 18, p. 439. See also discussion by H. W. McQuaid, Trans. Am. Soc. for Steel Treat., **13**, p. 1002; 1928.

TABLE 8.—*Impact resistance*[1] *of normal and abnormal steel and special manganese carburizing steel after various heat treatments*

Specimen No.[2]	Heat treatment					
	As received	Carburizing treatment[3]		Carburizing followed by treatment[4]		Treatment regenerative[3]
	Energy absorbed, in foot-pounds					
Normal steel:						
1M	72	16	21	85	79	77
8M	56	20	25	84	79	76
9M	72	24	26	89	81	84
11M	66	20	23	86	81	45
12M	73	30	36	92	84	87
14M	57	21	26	86	77	74
15M	73	19	31	90	81	83
18B	74	34	36	88	83	85
19M	75	20	19	93	86	89
21M	74	25	24	93	85	89
43	74	32	38	101	92	94
122	75	40	39	99	94	97
134	75	22	27	96	88	91
146	78	25	34	96	88	88
152	79	42	51	103	102	98
155	4	19	24	93	85	89
Abnormal steel:						
10T	70	36	40	86	59	74
13B	76	66	62	91	79	83
16M	73	45	46	87	80	84
113	79	73	61	97	91	96
119	71	62	60	110	96	104
125	72	69	74	94	89	96
131	73	35	55	102	95	92
137	76	67	71	95	88	91
143	81	54	76	101	95	98
149	82	54	62	115	109	114
E	68	32	45	89	75	----------
Special manganese carburizing steel J	51	61	70	81	78	78

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[1] A 120-foot-pound capacity Izod machine was used. The specimens were triple notched, and each value for energy absorbed is the average for the three notches.

[2] The chemical compostion of some of these specimens is given in Table 1, the compostion of the rest is given below:

Specimen No.	C	Mn	P	S	Si	Ni
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
1M	0.12	0.37	0.012	0.020	0.01	----------
8M	.11	.31	.013	.023	----------	----------
9M	.14	.31	----------	----------	.09	----------
11M	.12	.38	.012	.025	.01	----------
12M	.13	.41	----------	----------	.10	----------
14M	.12	.34	.010	.027	.005	----------
15M	.13	.36	----------	----------	.07	----------
18B	.12	.39	.013	.038	.08	----------
19M	.14	.35	.010	.024	.074	----------
21M	.12	.40	.012	.020	.068	----------
43	.17	.47	.018	.027	.14	0.18
10T	.12	.34	.013	.023	.01	----------
13B	.12	.39	.012	.025	.004	----------
16M	.13	.37	.010	.027	.008	----------

[3] By "carburizing treatment" is meant heating for eight hours at 940° C., and cooling in the furnace as in carburizing (no carburizer being used, however), after which the specimens were machined so that, if any oxidization occurred during the heating, the oxidized surfaces were removed.

[4] Regenerative treatment—oil quenching from 870° C., and drawing at 700° C.

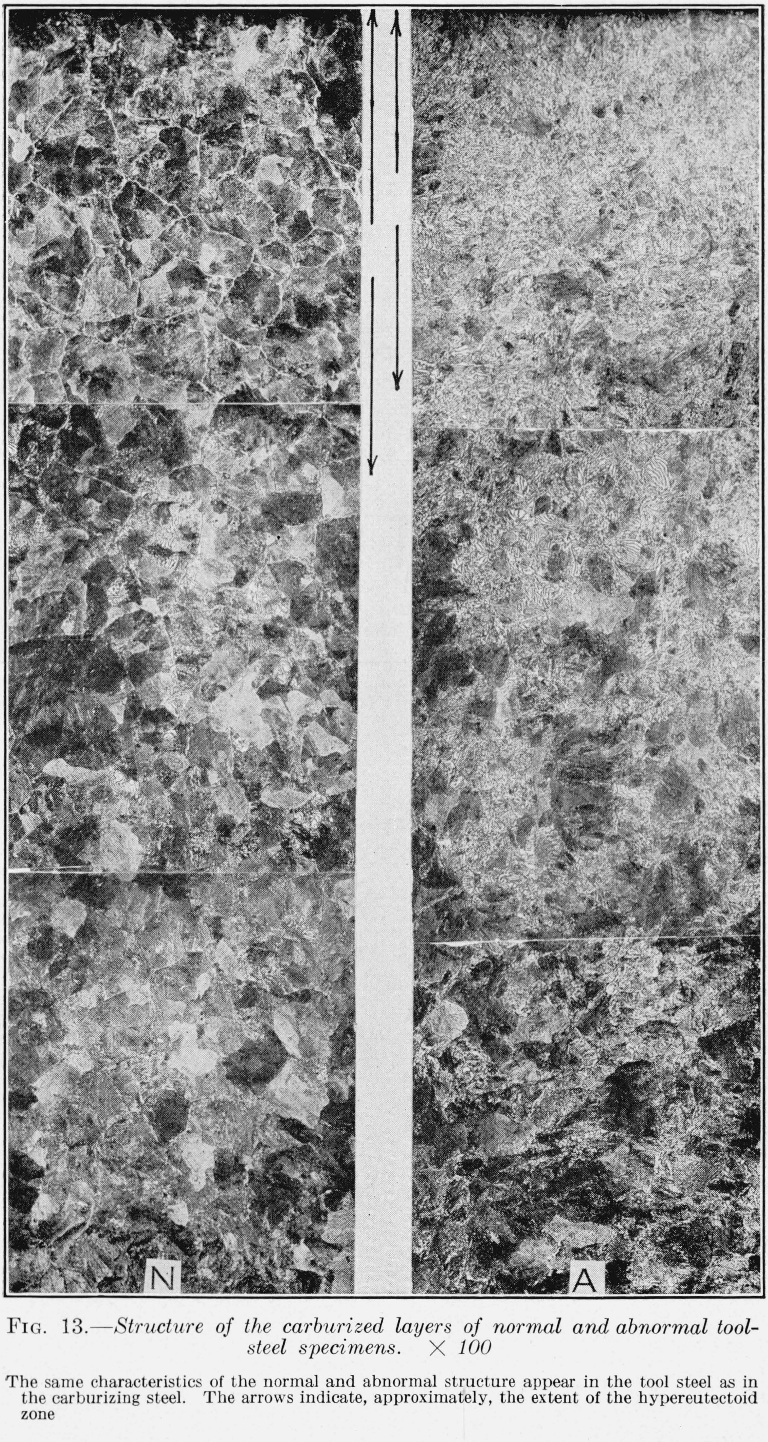

Fig. 13.—*Structure of the carburized layers of normal and abnormal tool-steel specimens.* × *100*

The same characteristics of the normal and abnormal structure appear in the tool steel as in the carburizing steel. The arrows indicate, approximately, the extent of the hypereutectoid zone

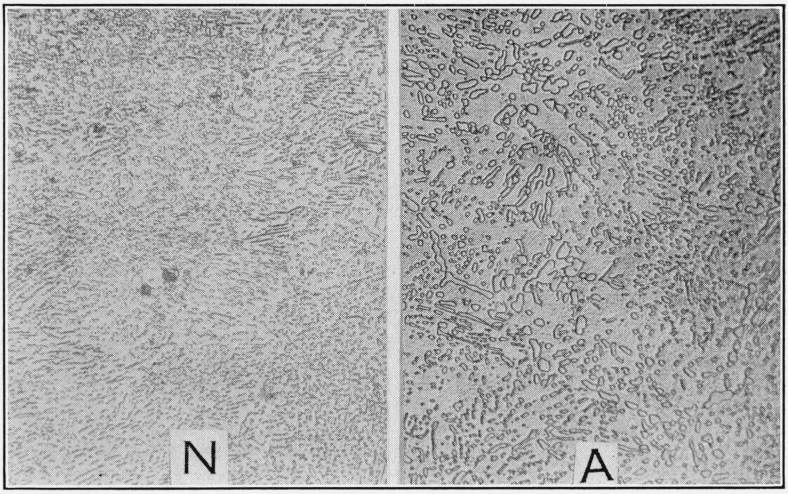

FIG. 14.—*The structure of normal and abnormal tool-steel specimens after cooling slowly through the critical range.* × *500*

The coalescence or spheroidization of the cementite has progressed further in the abnormal steel than in the normal steel. The specimens were cooled together

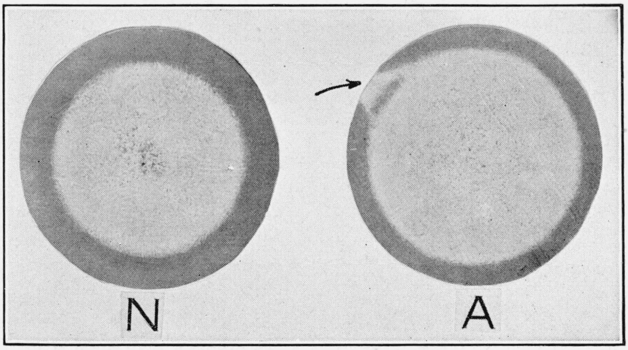

FIG. 15.—*Cross sections of quenched normal and abnormal tool-steel cylinders; deeply etched with hot 1 : 1 hydrochloric acid.* × *1*

The dark outer ring shows the depth of hardening. The arrow indicates a soft spot in the abnormal specimen. The two specimens were quenched simultaneously in the same bath

TABLE 9.—*Impact resistance*[1] *of normal and abnormal steel and special manganese carburizing steel, after quenching*[2]

Specimen No.[3]	⅛ inch from surface		½ inch from surface	
	Energy absorbed, in foot-pounds			
Normal steel:				
122	9	11	30	13
159	31	14	39	29
Abnormal steel: 113	76	62	88	77
Special manganese carburizing steel M	9	10	25	25
Special manganese carburizing steel J	22	14	38	24

[1] A 120-foot-pound capacity Izod machine was used. The specimens were triple notched, and each value for energy absorbed is the average for the three notches.

[2] Bars 1½ inches square, 6 inches long, were water quenched, from 775° C. after being given the "carburizing treatment." Izod impact specimens were then cut longitudinally from the bars, 1 impact specimen ⅛ inch from the surface and another ½ inch from the surface.

[3] The chemical compositions of these steels is given below:

Specimen No.	C	Mn	P	S	Si
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*
122	0.14	0.44	----------	----------	----------
159	.22	.53	0.018	0.048	0.02
113	.14	.42	----------	----------	----------

Special manganese carburizing steel J }
Special manganese carburizing steel M } See Tables 5 and 6.

V. NORMAL AND ABNORMAL TOOL STEEL

The characteristics of the normal and abnormal structure present in low-carbon carburizing steel have also been found to exist in high-carbon tool steel.[21] In order to bring out the differences between the normal and abnormal types, it is necessary to make the McQuaid-Ehn carburizing test with the tool steels just as with the carburizing steels.[22] Figure 13 shows the structures of a normal and abnormal tool steel of the following composition: Normal—C, 0.90 per cent; Mn, 0.28 per cent; Cr, 0.15 per cent. Abnormal—C, 0.90 per cent; Mn, 0.23 per cent; Cr, 0.01 per cent. The presence of the 0.15 per cent chromium in the normal steel (which apparently did not represent an intentional addition of chromium, the steel having been submitted as a plain carbon tool steel) makes it somewhat uncertain whether the more uniform hardening of the normal steel shown in Table 10 was due entirely to its structural normality or partly to the chromium content. In the above abnormal steel the tendency for coalescence of the cementite in the hypereutectoid zone manifested itself, after suitable treatment, also in the interior of the steel. Figure 14 shows the structure of samples of these normal and abnormal tool steels cooled together slowly through the critical range. It can

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[21] F. G. Sefing, "Abnormal *v.* Normal Tool Steels," Michigan State College, Eng. Exper. Station, Bull. No. 5.

[22] Acknowledgment is due to the Chicago Pneumatic Tool Co. and the Carpenter Steel Co. for furnishing specimens of tool steel.

be seen that in the abnormal steel the coalescence or spheroidization of the cementite has progressed further than in the normal steel. In this connection the thought suggests itself that the variation in the response to spheroidizing treatments of different samples of carbon steel of similar composition, noted by Whitley,[23] may have been connected with the normality or abnormality of the specimens used

In quenching tests of the above tool steels the abnormal samples showed themselves more prone to give soft spots than the normal samples; 1½-inch blocks similar to the carburized blocks could not be obtained, and instead smaller samples, 1¼-inch rounds, 2 inches long, were used. These gave fewer soft spots than the larger carburized blocks, but, as shown in Table 10, the indications were that the abnormal samples were more prone to give soft spots. Brine quenching was not used with the tool steels, since it was evident from the preceding work that complete hardening would be obtained in this way.

TABLE 10.—*Index numbers [1] of soft spots of normal and abnormal tool steels [2]*

Pair No.	Heating bath	Quenched		Index number of soft spots	
		In—	At—	Normal	Abnormal
			° C.		
1	Air atmosphere	Tap water	29	0	31
2	do	do	28	1	30
3	do	do	17	0	3
4	do	do	17	0	0
5	do	do	17	1	1
6	Cyanide salt bath	do	28	0	15
7	do	do	28	0	14
8	do	do	20	0	0
9	do	do	19	0	2
10	do	do	28	0	22
11	do	do	28	0	3
12	do	Tap water plus oxygen	28	0	7
13	do	do	28	0	24
14	do	do	30	0	20
15	do	do	30	0	30

[1] 1¼-inch rounds, 2 inches long, were used. Ninety-six Rockwell readings were taken on each specimen, as with the carburized blocks. The specimens were heated for 30 minutes at 775° C. before quenching.

[2] The composition is given below:

Normal: C, 0.90 per cent; Mn, 0.28 per cent; Cr, 0.15 per cent.
Abnormal: C, 0.90 per cent; Mn, 0.23 per cent; Cr, 0.01 per cent.

Figure 15 shows cross sections of quenched samples of the above normal and abnormal tool steels deeply etched with 1:1 hydrochloric acid. The dark outer ring in each specimen shows the depth of the hardened layer. The normal steel hardened considerably more deeply than the abnormal steel. An arrow indicates a soft spot in the abnormal steel. Here again it is uncertain whether the greater depth of hardening of the normal steel was due entirely to its struc-

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[23] J. H. Whitely, "The formation of globular pearlite," Iron & Steel Inst., **105**, p. 346, 1922.

tural normality or partly to its chromium content. It is to be regretted that specimens of normal and abnormal tool steel of exactly similar composition could not be obtained for these tests. At any rate it appears that, on account of the possible variations in the content of carbon, manganese, chromium, etc., in carbon tool steels, the chemical composition may be as important in determining the critical cooling rate necessary for complete hardening as the structural normality.

Practically, as has already been pointed out for carburized steels, different degrees of normality may be desired also for tool steels, depending on the purpose for which they are to be used. For example, for penumatic tools a less deeply hardening steel is preferred, to counteract brittleness.

The experimental work so far described shows that there exist in steels differencies, of which the most sensitive indication is the microstructure of the carburized layer. A definition of abnormality could, however, be made on the basic of the critical cooling rate necessary for hardening after carburizing. The connection between abnormality thus defined and soft spots would then be obvious—no soft spots would occur if the critical cooling rate were exceeded. The microstructure and the critical cooling rate are undoubtedly two different manifestations of the same underlying cause.

VI. CAUSES OF ABNORMALITY

According to Ehn, abnormality is caused by dissolved or submicroscopic particles of oxides. In discussion of his work other causes were suggested, such as high nitrogen content and high phosphorus content. Indeed, in tests at the Bureau of Standards it has been found that almost any pronounced irregularity in chemical composition of the specimen is plainly reflected in the appearance of the carburized structure. Thus, the structure of wrought iron, of electrolytic iron, of highly phosphorized, oxidized, or nitrogenized iron, of the fused-in metal of welds,[24] of small steel ingots low in manganese melted in a laboratory induction furnace, and of unfinished steel sampled in the progress of a heat, all showed marked differences after carburizing from the structures of normal steel. From this viewpoint there may be any number of causes for structural abnormality of steel. It must be noted, however, that most of the above-mentioned causes would hardly apply to commercial steel.

In commercial steel we need consider as possible causes of abnormality only such factors as are present in everyday steel making; we must be careful not to infer too readily that because a thing causes abnormality in a laboratory sample it is consequently a cause of abnormality in commercial steel. For instance, in laboratory melts

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[24] See footnote 3, p. 425.

excessive phosphorus content causes an abnormal structure. It does not follow, however, that phosphorus is a cause of abnormality in commercial steel; actually, as shown by chemical analyses of commercial normal and abnormal steel, there seems to be no relation between the phosphorus content and abnormality. Again, in laboratory melts low manganese content, especially when accompanied by low carbon content,[25] gave an abnormal structure. Low manganese content, however, can hardly be regarded as a cause of abnormality in commercial steel, for, as shown by chemical analyses of ordinary commercial normal and abnormal steels, there seems to be no obvious relation between the manganese content and abnormality. Similarly, it was found in laboratory experiments[26] that excessive oxygen content caused an abnormal structure. Here, also, we must realize we are not justified in concluding that abnormality is caused by high oxygen content, unless analyses of representative abnormal steel specimens actually show a high oxygen content. It is not enough to show that some abnormal steel has a high oxygen content, for such specimens may be exceptional. To justify the conclusion that abnormal steel is caused by high oxygen content, it must be shown that the general run of abnormal steel is high in oxygen. Due regard for these considerations would help remove much of the existing confusion as to the causes of abnormality in commercial steel.

The chief difficulty involved in the subject of the relation between abnormality and oxygen content is due to the imperfect state of the methods of oxygen analysis. Ehn did not try to show any quantitative relation between abnormality and oxygen content but suggested instead that abnormality is not due primarily to the amount of oxides present in the steel, but to their type and form—in particular, that the oxides effective in causing abnormality are present in solution or as colloidal or submicroscopic particles. In this form, Ehn's explanation of abnormality is not readily capable of quantitative verification. In spite of the decided improvements that have recently been made in the methods of oxygen analysis, it has not yet been possible to find a quantitative relation between abnormality and oxygen content. In the present work, during the gathering of data bearing on the causes of abnormality, nothing has arisen to weaken Ehn's theory; on the contrary, the data tend rather to support it, and, although not definitely established, it continues to be a helpful guiding principle. Below are given the results of the work done in this investigation to determine the cause of abnormality.

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[25] Unpublished results by the Bureau of Mines.

[26] In tests at the Bureau of Standards electrolytic iron, remelted in an induction furnace in air, showed an extremely abnormal structure. See also Harder, Weber, and Jerabek, footnote 9, p. 430; they found that steel heated in oxygen became very abnormal.

1. SPECTROGRAPHIC ANALYSES FOR ALUMINUM

Ordinary chemical analyses have failed to show any relation between abnormality and the amounts of the usual elements determined in steel—namely, sulphur, manganese, phosphorus, and silicon—so that abnormality can hardly be ascribed to variations in content of these usual elements. A relation was found, however, between aluminum content (probably more strictly, alumina content) and abnormality. It had been observed in a rather extensive series of preliminary experiments [27] that steel treated with aluminum in the mold was abnormal. In spectrographic analyses[28] of a large number of commercial normal and abnormal steel specimens it was likewise found that abnormality was generally associated with high aluminum content. Figure 16 shows the results of these spectrographic analyses. The intensity of the aluminum lines in the arc spectrum of the specimen is proportional to the aluminum content. With the aid of chemical analyses [29] of a series of specimens of varying aluminum content, a given intensity of the aluminum lines in the spectrum was

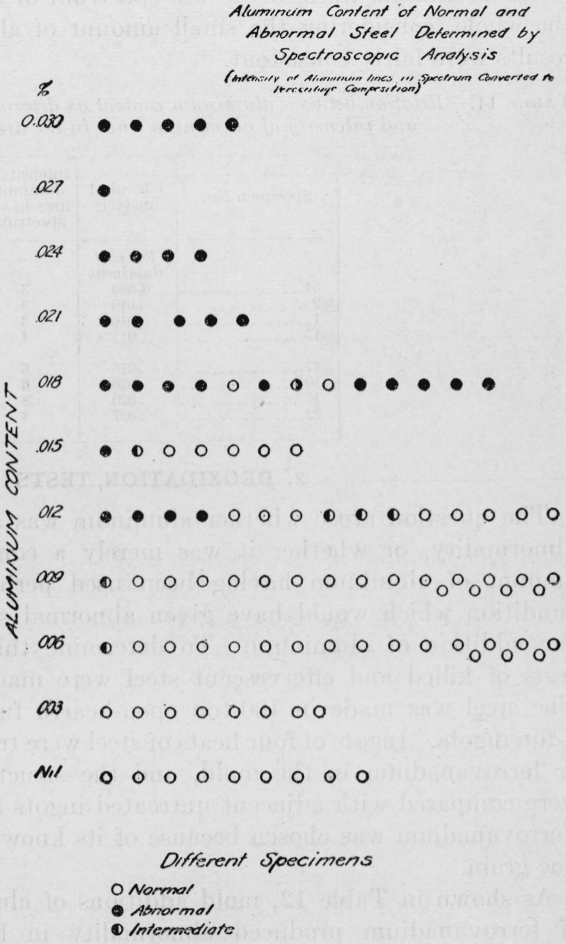

FIG. 16.—*Results of spectrographic analyses for aluminum of normal and abnormal steel specimens*

About half of the specimens were commercial steels; the other half, though experimental, were made on a commercial scale in 100-ton furnaces.

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[27] Acknowledgment is due to the Trumbull Steel Co., at whose plant the experiments were made, and to the Titanium Alloy Manufacturing Co. and the Union Carbide & Carbon Co., who cooperated.

[28] Spectrographic analyses by W. F. Meggers, physicist, Bureau of Standards.

[29] H. A. Bright, associate chemist, Bureau of Standards.

converted to percentage composition of aluminum. Unfortunately for the general utility of the spectrographic method, it appears that consistent results can be obtained only after much experience.

Table 11 shows the interrelation between the results of the chemical analyses for aluminum of a number of specimens and the intensity of the aluminum lines in the arc spectrum of these specimens. On the whole, considering the small amount of aluminum present, the results were fairly consistent.

TABLE 11.—*Relation between aluminum content as determined by chemical analysis and intensity of aluminum lines in the arc spectrum*

Specimen No.	Chemical analysis	Intensity of aluminum lines in arc spectrum
	Per cent aluminum	
54	0.009	3
2	.010	3
1	.010	3
15	.011	4
47	.016	6
10B	.026	6
E	.020	8
22	.027	8

2. DEOXIDATION TESTS

The question arose whether aluminum was actually the cause of abnormality, or whether it was merely a concomitant, the larger amount of aluminum having been used perhaps to counteract a condition which would have given abnormal steel with or without the addition of aluminum. To determine this point, deoxidation tests of killed and effervescent steel were made at a steel plant.[30] The steel was made in 100-ton open-hearth furnaces and cast into 3-ton ingots. Ingots of four heats of steel were treated with aluminum or ferrovanadium in the mold, and the structures of these ingots were compared with adjacent untreated ingots from the same heats. Ferrovanadium was chosen because of its known effect in producing fine grain.

As shown in Table 12, mold additions of aluminum and likewise of ferrovanadium produced abnormality in both the killed and effervescent steel. The additions of aluminum and ferrovanadium used in the mold were just sufficient to kill the ingots of effervescent steel. Figures 17, 18, 19, and 20 show micrographs of the carburized layers of bars from the regular ingots of the killed and effervescent steels and of bars from ingots of the same heats, treated with aluminum or ferrovanadium in the mold. The samples from the untreated ingots were normal; those from the treated ingots were abnormal. In the carburized layers of the untreated effervescent steel samples

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[30] These tests were made possible through the courtesy of the Central Alloy Steel Corporation, Canton Ohio.

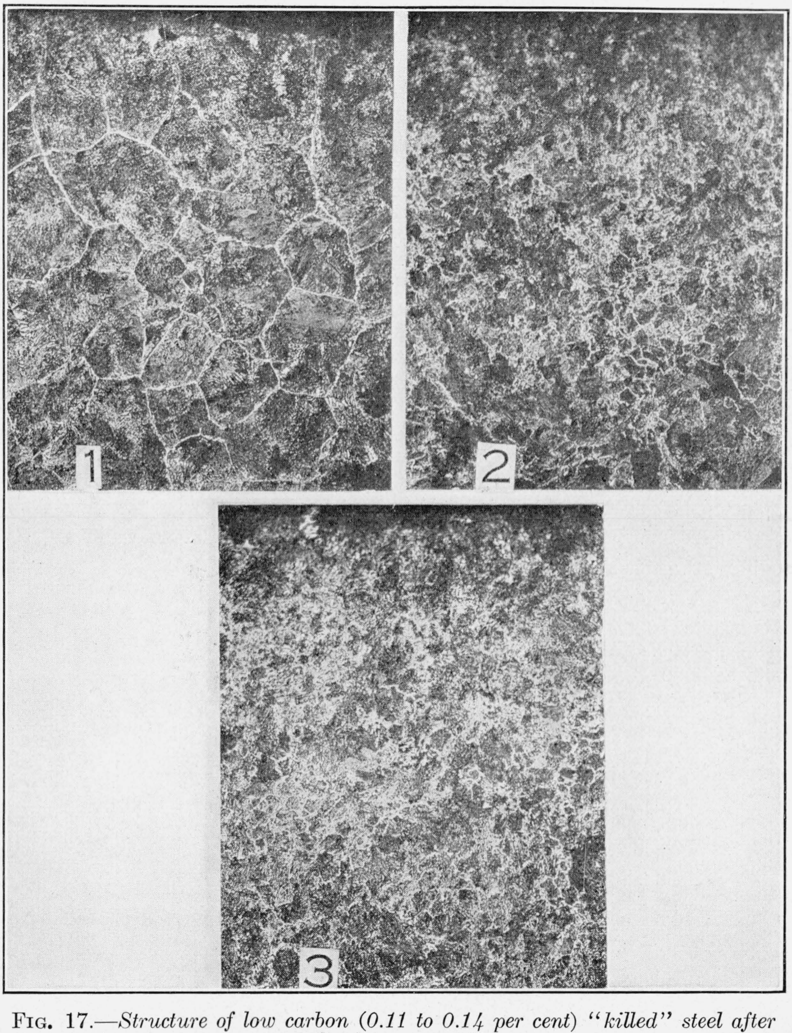

FIG. 17.—*Structure of low carbon (0.11 to 0.14 per cent) "killed" steel after carburizing.* × *100*

The steel was killed by the use of ferrosilicon; *1*, forged down from regular commercial ingot; normal; *2*, forged down from 3-ton ingot from same heat with 4 pounds of shot aluminum added in mold; abnormal; *3*, forged down from 3-ton ingot from same heat with 25 pounds of 37 per cent ferrovanadium added in mold; abnormal

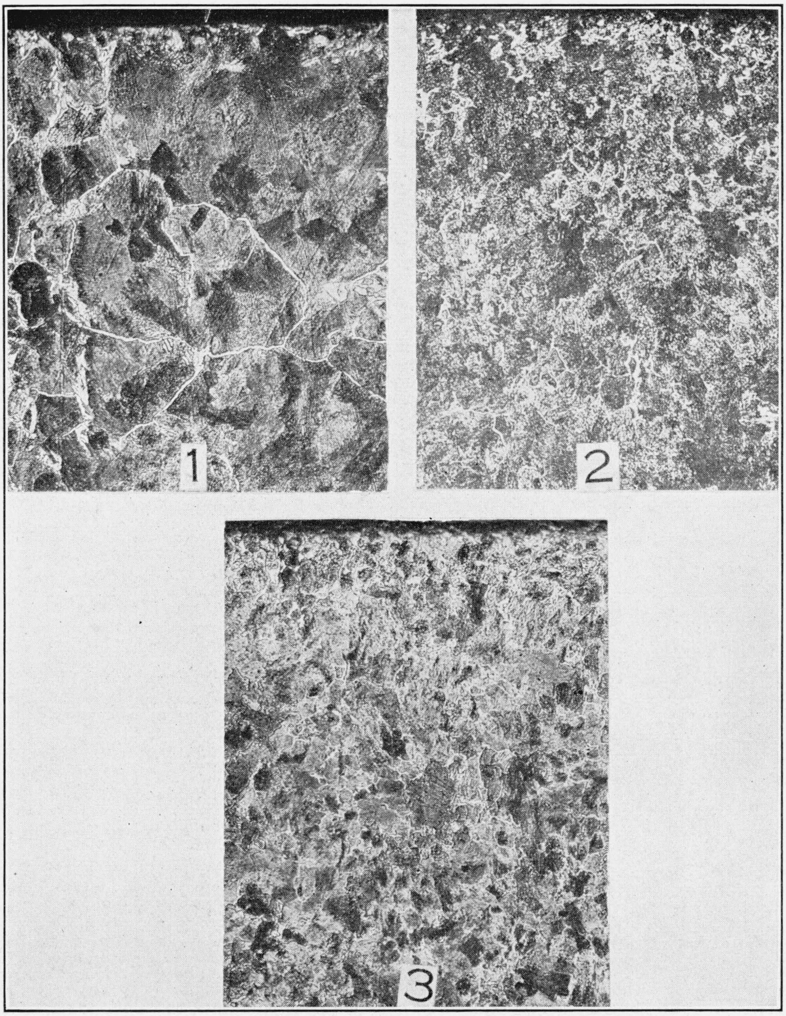

FIG. 18.—*Structure of low carbon (0.11 to 0.14 per cent) effervescent steel after carburizing.* × *100*

1, forged down from regular commercial ingot; normal; *2*, forged down from 3-ton ingot from same heat with 4 pounds of shot aluminum added in mold; abnormal; *3*, forged down from 3-ton ingot from same heat with 25 pounds of 37 per cent ferrovanadium added in mold; abnormal

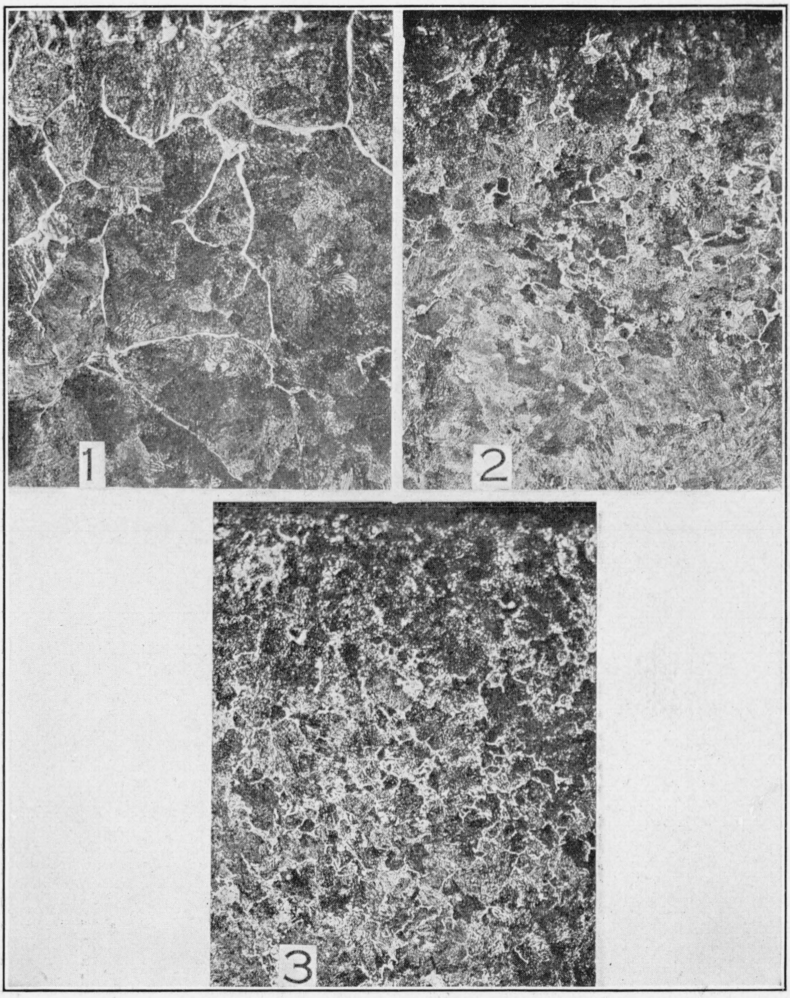

FIG. 19.—*Structure of low carbon (0.11 to 0.14 per cent) effervescent steel after carburizing.* × *100*

1, forged down from regular commercial ingot; normal; *2,* forged down from 3-ton ingot from same heat with 5 pounds shot aluminum added in mold; abnormal; *3,* forged down from 3-ton ingot from same heat with 25 pounds of 37 per cent ferrovanadium and 1½ pounds of shot aluminum added in mold; abnormal

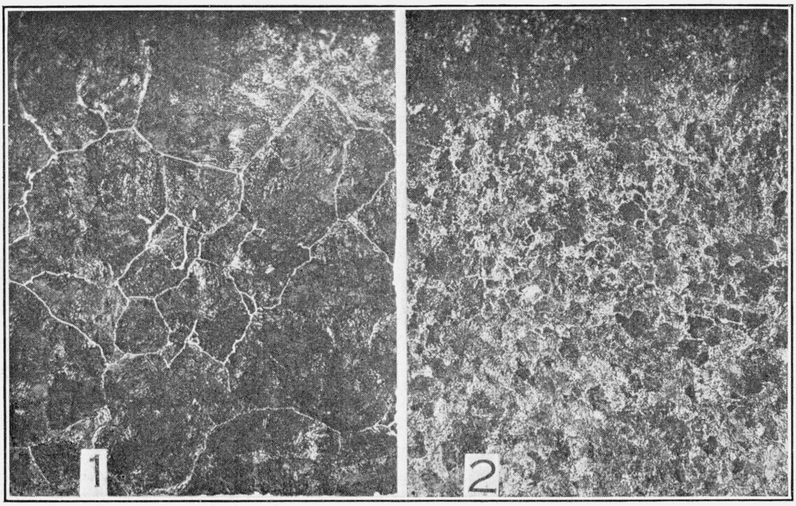

FIG. 20.—*Structure of one-half per cent nickel "killed" steel after carburizing.* × *100*

1, forged down from regular commercial ingot; normal; *2*, forged down from 3-ton ingot from same heat with 25 pounds of 37 per cent ferrovanadium added in mold; abnormal

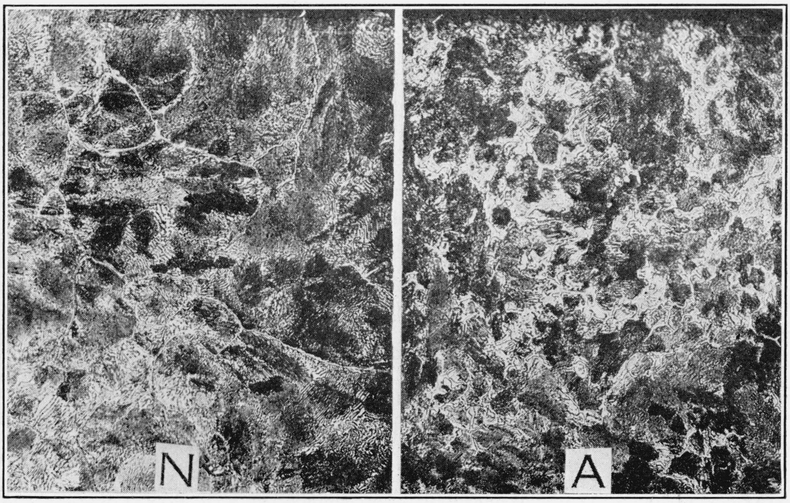

FIG. 21.—*Structure of the carburized layers of two ingots of 0.12 per cent carbon effervescent steel from the same heat, the ingots deoxidized with silicon in the mold and aluminum in the mold, respectively.* × *100*

The silicon treated steel is normal; the aluminum treated steel is abnormal the cementite envelopes were somewhat thicker than in the untreated killed steel samples; the grain size was large, however, with no marked separation of the cementite from the ferrite, so that it appears justifiable to classify the untreated effervescent samples as normal. The important point was noted that in the killed steel about the same amount of aluminum per ton of steel was added in the ladle, as a matter of regular practice, as was used in the experimental mold additions to the killed and effervescent steels. However, in contrast to the mold additions, the ladle additions apparently did not produce abnormality. The effect of either the aluminum or ferrovanadium additions appeared to be the same with the killed steels, to which aluminum had already been added in the ladle, as with the effervescent steels, to which no aluminum additions had previously been made.

TABLE 12.—*Effect on degree of normality of additions of aluminum or ferrovanadium in the mold to successive ingots of heats of killed and effervescent steel*

Type of steel	Ingot No.	Mold addition to 3-ton ingot	Structure of carburized layer
Heat 1, 0.11 to 0.14 per cent C, killed steel	7	4 pounds shot Al	Abnormal.
	8	do	Do.
	9	25 pounds 37 per cent ferrovanadium	Do.
	10	Regular ingot, no mold addition	Normal.
Heat 2, 0.11 to 0.14 per cent C, effervescent steel.	7	4 pounds shot Al	Abnormal.
	8	do	Do.
	9	25 pounds 37 per cent ferrovanadium	Do.
	10	Regular ingot, no mold addition	Normal.
Heat 3, 0.11 to 0.14 per cent C, effervescent steel.	7	5 pounds shot Al	Abnormal.
	8	do	Do.
	9	25 pounds 37 per cent ferrovanadium 1½ pounds shot Al.	Do.
	10	Regular ingot, no mold addition	Normal.
Heat 4, 0.13 to 0.16 C, 1½ per cent Ni, killed steel.	7	25 pounds ferrovanadium	Abnormal.
	8	Regular ingot, no mold addition	Normal.

In previous tests it was found that the effect of silicon was quite different from that of aluminum. Figure 21 shows micrographs of the carburized layers of two ingots of 0.12 per cent carbon effervescent steel from the same heat, the ingots killed in the mold with ferrosilicon and aluminum respectively. The silicon-treated steel was normal; the aluminum-treated steel was abnormal. The idea should not be gained, however, that a very low silicon content, say below 0.01 per cent, such as is found in ingot iron and in much effervescent steel, in itself produces abnormality, and that the presence of larger amounts of silicon produces normality. Perusal of the tables of chemical compositions given in this paper will show that this is not true; for example, in Table 13 steels A and E, with over 0.20 per cent silicon, were abnormal and steel R, with only 0.002 per cent silicon, was normal.[31]

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[31] Steels (High Silicon Structural Steel, H. W. Gillett, B. S. Tech. Paper No. 331, p. 129, 1926) of about 0.11 per cent C, 0.90 per cent Si, with about 0.50 to 0.80 per cent Mn, containing as well 0.02 to 0.03 per cent Al., were classed as intermediate or fine-grained normal.

The results given in Table 12 clearly indicate that abnormality, if it is not caused directly by oxides in the steel, is at least closely associated with the manner of deoxidation. It is significant that ladle additions of aluminum did not produce abnormality, whereas mold additions did. In both instances a large proportion of the aluminum may be presumed to have become oxidized, and it appears very probable that the difference in effect may be due to a difference in the form or size of the oxide particle, the finer particles causing abnormality. When aluminum is added in the large 100-ton ladle the aluminum oxide has a chance to coalesce into larger particles and rise to the slag. When aluminum is added in the mold, however, the oxide particles are more likely to remain in a fine state of subdivision than when the addition is made earlier; that is, in the ladle. The difference in action between silicon and aluminum may, perhaps, be accounted for similarly. The oxides formed from the addition of silicon were probably more fusible than those formed from the addition of aluminum and may, therefore, more readily coalesce into larger particles. It has also been suggested that perhaps the reason why the addition of aluminum in the ladel did not produce abnormality was that this aluminum, instead of forming alumina, reacted to form aluminum silicates with the regular addition of ferrosilicon which was added in the ladle at the same time.

An interesting observation of the deoxidation tests was that additions of aluminum gave similar results in respect to abnormality as additions of ferrovanadium. The effect of vanadium in producing fine grain is well known and is probably largely due to obstruction to grain gowth by fine particles of vanadium compounds, perhaps oxides or carbides. The vanadium-treated steels gave the same number of soft spots in quenching tests and hardness surveys as the aluminum-treated steels. Aluminum-treated abnormal specimens showed the same superior impact resistance to normal steel, as ferrovanadium treated abnormal steel. (See Sec. IV.) The suggestion presents itself that the effect of an expensive alloying element, such as vanadium, in producing the desirable property of fine grain, may be simulated by inexpensive additions of aluminum to both alloy and plain carbon steel. Of course, the disadvantage of aluminum is the tendency of its oxides to segregate, but this might, perhaps, be counteracted by adding the aluminum in less concentrated form, perhaps as an alloy with iron, and in the minimum amount that will produce the effect. However, the uncertainty as to the oxygen content of the steel at the moment of adding the aluminum would no doubt make it very difficult to get dependable results.

3. EXAMINATION OF SMALL TEST INGOTS TAKEN DURING PROGRESS OF OPEN-HEARTH HEATS

The deoxidation tests described above plainly indicate that abnormality may be due to the manner of deoxidation. A series of McQuaid-Ehn tests of very small test ingots taken during the progress of open-hearth heats appeared to indicate that in finished steel the deoxidation treatment is the main factor, apparently overshadowing any differences in the degree of normality that may have been produced during the melting and refining of the steel. Figure 22 shows the carburized layers of a series of small test ingots from an open-hearth heat of 0.20 per cent carbon killed steel. It can be seen that samples taken during the refining of the heat showed decided coalescence of the cementite. After deoxidation, however, the steel seemed to be perfectly normal, the degree of normality apparently reflecting mainly the deoxidizing treatment used. Figure 23 shows the carburized layers of a series of small test ingots from another open-hearth heat in which samples taken during the progress of the heat showed very little coalescence of the cementite. This steel, after deoxidation, was likewise normal.

The fact (discussed under II, 5) that variations in the mechanical treatment and heat treatment of steel have practically no effect on the degree of normality indicated that abnormality has its origin in the making of the steel. The experiments above indicated that in the heats of steel tested the degree of normality of the finished steel was more largely dependent on the deoxidation procedure than on the melting procedure. The results obtained in the deoxidation tests with aluminum bear out the results of the spectrographic analyses, which showed that abnormality in commercial plain carbon carburizing steel was almost invariably accompanied by a high aluminum content. From the above, and in view of the common use of aluminum in the deoxidation of steel, the conclusion appears justifiable that most cases of abnormality in commercial steel are due to aluminum oxide

4. OXYGEN ANALYSES

Although abnormality was shown to be connected with the deoxidation procedure, no direct relation was found between oxygen content and abnormality. Table 13 gives the results of gas analyses by the vacuum-fusion method [32] of representative specimens of commercial normal and abnormal steel. There is no noticeable relation between the nitrogen or hydrogen contents and abnormality. To visualize better the results of the oxygen analyses, the specimens in Table 13 have been divided into two groups of lower and higher

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[32] L. Jordan and J. R. Eckman, B. S. Sci. Paper No. 514. Gases in Metals, II. The Determination of Oxygen and Hydrogen in Metals by Fusion in Vacuum.

apparent oxygen content, respectively. It can be seen that abnormal specimens do not as a rule show higher apparent oxygen content; on the contrary, most of them fall into Group I of lower apparent oxygen content. The values given are for apparent oxygen content as determined by the original vacuum-fusion method. They give no information about the form in which the oxygen determined is present in the steel, whether in solution or as inclusions; and if as inclusions, whether these are compounds of iron, manganese, or silicon, for example.

TABLE 13.—*Results of gas analyses of normal and abnormal steel specimens* [1]

Specimen No.	Structure of case	Chemical composition					Gas content (uncarburized stock)		
		C	Mn	P	S	Si	N_2[2]	H_2[3]	Apparent O_2[3]
	Group I (lower oxygen content):	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
A	Abnormal	0.23	0.52	0.027	0.030	0.23	0.012	(4)	(4)
B	Intermediate	.21	.52	.032	.030	.19	.009	(4)	(4)
C	Abnormal	.46	.71	------	------	------	------	0.0002	(4)
D	Do	.19	.48	.028	.025	.06	.015	.0001	0.002
E	Do	.21	.51	.024	.029	.22	.011	.0001	.002
F	Intermediate	.21	.43	.009	.042	.006	.005	.004	.003
G	Abnormal	.16	.42	------	------	------	.003	------	.003
H	Normal	.17	.43	------	------	------	------	(4)	.002
I	Do	.14	.51	------	------	------	------	(4)	.003
J	Do	.21	.17	------	------	------	------	.0001	.003
K	Abnormal	.19	.42	.009	.043	.006	.003	(4)	.003
L	Do	.22	.41	------	------	------	------	------	.004
M	Do	.19	.48	.004	.027	.03	.005	.0005	.005
N	Do	.26	.52	.019	.036	.009	.004	.0004	.006
O	Do	.12	.34	------	------	.01	------	.0006	.003
P	Do	.12	.39	------	------	.004	------	.0009	.003
Q	Do	.13	.37	------	------	.008	------	(4)	(4)
	Group II (higher oxygen content):								
R	Normal	.19	.41	.004	.050	.002	------	.001	.009
S	Do	.16	.44	.009	.019	.05	.005	.0007	.011
T	Do	.25	.46	.014	.027	.13	.004	.0007	.012
U	Do	.17	.60	.012	.021	.03	.004	.0006	.012
V	Abnormal	.08	.33	------	------	------	------	.0005	.017
W	Do	.07	.37	.014	.021	.013	.010	(4)	.032
X	Normal	.12	.37	------	------	.01	------	.0004	.008
Y	Do	.12	.27	------	------	.07	------	(4)	.037
Z	Do	.12	.28	------	------	------	------	.0007	.012
AA	Do	.12	.38	------	------	.08	------	.0001	.018
BB	Do	.14	.35	------	------	.07	------	.0001	.017
CC	Do	.14	.25	------	------	.07	------	.0001	.021

[1] Analyses by W. P. Barrows, assistant chemist, and R. J. Kranauer, assistant scientific aid, Bureau of Standards.

[2] Combined nitrogen by the Allen method.

[3] Apparent oxygen and hydrogen by the vacuum-fusion method.

[4] Not detected.

The fact that most of the abnormal specimens in Table 13 showed lower apparent oxygen content than the normal specimens requires further mention. As we have seen, the commercial abnormal steels were generally high in aluminum. It is quite certain that aluminum oxide, which, presumably, was present in these abnormal steels, is

FIG. 22.—*Change in degree of normality in commercial steel accompanying deoxidation.* × *100*

1 to *5*, carburized layers of small test ingots taken during the progress of a 0.20 per cent carbon steel open-hearth heat. These test ingots were taken at half-hour intervals during three hours prior to tapping the heat. The micrographs show that this heat before deoxidation was pronouncedly abnormal; *6*, carburized layer of the finished steel after deoxidation; the structure is normal

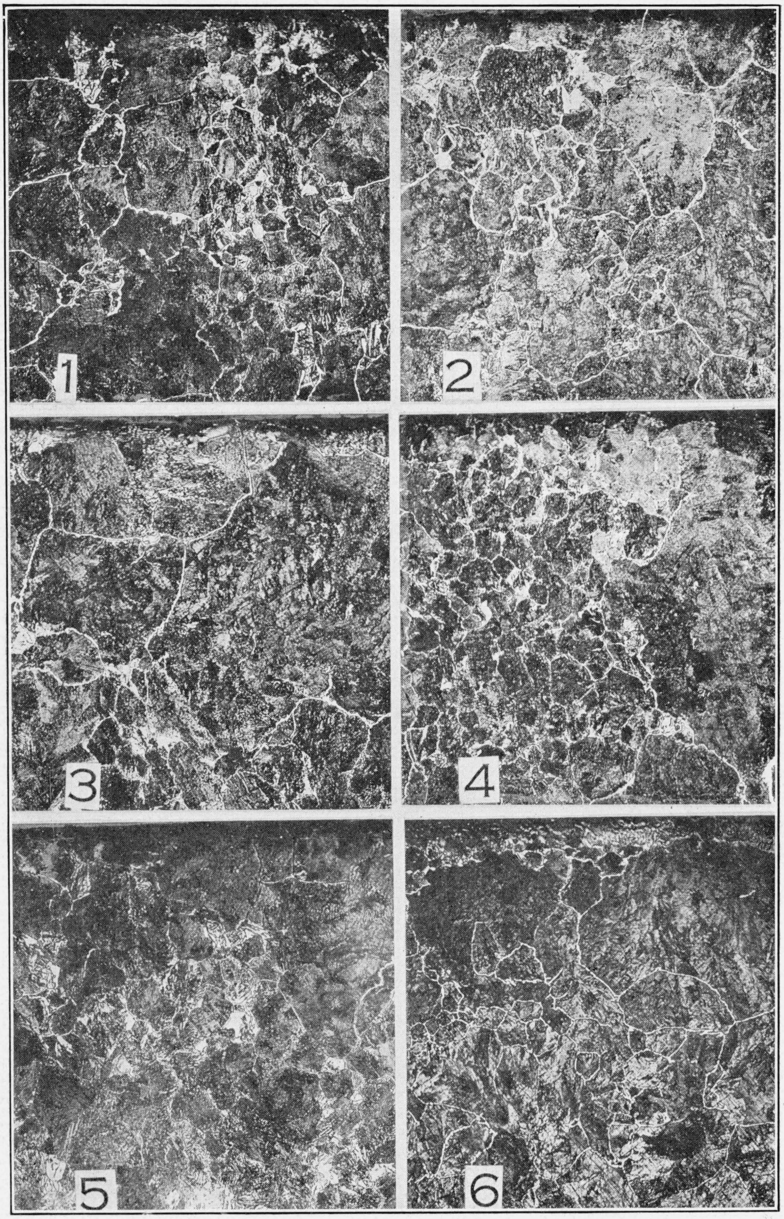

Fig. 23.—*Commercial steel which showed no marked change in normality during deoxidation.* × *100*

1 to *5*, carburized layers of small test ingots taken during the progress of a 0.30 per cent carbon, 0.60 per cent chromium, and 1 per cent nickel steel open-hearth heat. These test ingots were taken at half-hour intervals during three hours prior to tapping the heat. This heat did not appear to go through a pronouncedly abnormal stage, as did the heat shown in Figure 24. The structures *1* to *5* may be called almost normal; *6*, the carburized layer of the finished steel after deoxidation; the structure is likewise normal not completely reduced during the analysis by the vacuum-fusion method, and it follows that the abnormal specimens of Table 13 probably have a higher total oxygen content than that indicated by the analysis. This is well borne out by oxygen analyses by the vacuum-fusion method of the steels treated with aluminum and ferrovanadium in the mold and of adjacent untreated ingots, as shown in Table 14. After the addition of aluminum in the mold, the apparent oxygen content in the steel was negligible, although the oxygen content of the regular untreated ingots from the same heats was not unusual. It should be noted, in the first two heats, that there was no change in the oxygen content from that of the regular untreated steel when ferrovanadium was added. In the third heat less oxygen was found in the ferrovanadium-treated ingot, but this ingot had been treated with some aluminum as well. Apparently any oxygen present in these specimens as vanadium oxide was recovered.

TABLE 14.—*Change in apparent oxygen content, as determined by the vacuum-fusion method, produced by addition of aluminum or ferrovanadium in the mold of successive ingots of heats of killed and effervescent steel*

[Al_2O_3 content of the first six specimens shown in last column]

Type of steel	Ingot No.	Mold addition to 3-ton ingot	Structure of carburized layer	Oxygen content O_2	Al_2O_3 content
				Per cent	*Per cent*
Heat 1, 0.11 to 0.14 per cent C, killed steel.	8	4 pounds shot aluminum	Abnormal	(1)	0.025
	9	25 pounds 37 percent ferrovanadium	do	0.003	.003
	10	Regular ingot, no mold addition	Normal	.003	.002
Heat 2, 0.11 to 0.14 per cent C, effervescing steel.	8	4 pounds shot aluminum	Abnormal	(1)	.014
	9	25 pounds 37 per cent ferrovanadium	do	.011	.002
	10	Regular ingot, no mold addition	Normal	.010	.001
Heat 3, 0.11 to 0.14 per cent C, effervescing steel.	8	5 pounds shot aluminum	Abnormal	(1)	----------
	9	25 pounds ferrovanadium, 1½ pounds shot aluminum.	do	.002	----------
	10	Regular ingot, no mold addition	Normal	.009	----------
Heat 4, 0.13 to 0.16 per cent C, ½ per cent Ni, killed steel.	7	25 pounds 37 per cent ferrovanadium	Abnormal	.013	----------
	8	Regular ingot, no mold addition	Normal	.009	----------

[1] Not detected.

Residue analyses[33] for Al_2O_3 by the hydrochloric-acid method described by Oberhoffer and Amman[34] were made of the first six specimens in Table 14; the results are shown in the last column of that table. The aluminum-treated specimens of both the killed and effervescent steel heats contained appreciable amounts of Al_2O_3. However, the oxygen content in the Al_2O_3 in these specimens (about half by weight of the Al_2O_3) is approximately equal to and by no means greater than the general run of oxygen content of the normal specimens shown in Table 13. The conclusion appears warranted that

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[33] Analyses by R. J. Kranauer, assistant scientific aide, Bureau of Standards.

[34] Stahl und Eisen, **47**, pp. 1536–1540; 1927.

in commercial carburizing steels there is no direct relation between the total oxygen content and abnormality.

Gat[35] has reported that abnormal steel usually contains much more oxygen than normal steel. This is not borne out by the results at the bureau. Almost all of the normal and abnormal steel specimens analyzed at the bureau had the same range of oxygen content as Gat's normal specimens. His abnormal specimens, however, had unusually high oxygen content. (It should be noted that his analyses were made by identically the same method as that formerly used at the Bureau of Standards, which gives only "apparent" oxygen—not that combined as Al_2O_3, so that his experimental evidence is on just the same basis as that of Table 13.) It is indeed possible that the unusually high oxygen content in Gat's abnormal specimens produced the abnormal structure. However, as pointed out in the preliminary discussion of the causes of abnormality, it would be an error in logic to conclude, because an unusually high oxygen content makes steel abnormal, that all or most commercial abnormal steel has a high oxygen content. As shown in Table 13, only 1 out of 14 representative specimens of commercial abnormal steel was found to have a high apparent oxygen content; the rest had an apparent oxygen content as low as or lower than normal steel.

There is, from all the accumulated evidence, no sharp dividing line between normal and abnormal steel on the sole basis of the content in the steel of any single element. The composition as to carbon, manganese, silicon, phosphorus, sulphur (through its effect in binding manganese), aluminum, and oxygen seems to play an indirect part, the governing factor apparently being not the total amount of any element or combination of elements present, but the form of the element or combination of elements. It is not yet possible to determine exactly the total oxygen content of steels containing aluminum, and, even if this could be done, the question as to how much of the oxygen is combined with each of the elements present in the steel would still remain, as would also the question of the size of the various oxide particles.

5. THE SO-CALLED "IRON-CARBON-OXYGEN EUTECTOID"

Gat[35] has concluded that the ferrite which surrounds the hypereutectoid cementite in the carburized layer of abnormal steel is not true ferrite, but an "iron-carbon-oxygen eutectoid," and that abnormality is due to this eutectoid. The only evidence in his paper of the existence of such a constituent was a micrograph of the carburized layer of abnormal steel, rather deeply etched. The constituent surrounding the cementite had a mottled appearance, and

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[35] See footnote 5, p. 427.

this was declared to be the "eutectoid." An indistinct needle scratch across the micrograph was also shown, and it was stated the scratch indicated the eutectoid to be harder than ferrite and of about the same hardness as pearlite. It was pointed out in the discussion[37] that overetched ferrite nearly always has the mottled appearance shown, and that ferrite not well polished may have the same appearance even when not overetched. The unreliability of the scratch test in the case at hand was also pointed out. Gat, in his reply to the discussion, submitted additional micrographs showing the appearance of the "eutectoid." In the first micrograph shown the "eutectoid" seemed to be simply ferrite; in these additional micrographs, on the contrary, the "eutectoid" seemed to be nothing but cementite. It had the characteristic shape of coalesced cementite in low-carbon steel, it polished in relief, and it etched dark with sodium picrate. Gat states that in a very low-carbon steel of 0.02 per cent carbon content there was very little of this constituent, but that there was more in steels of higher carbon content. Naturally, the higher carbon steel would have more cementite.

In polished iron or low-carbon steel some of the grains of ferrite often show a mottled appearance, and one is led to wonder whether these mottled grains are different from the rest of the ferrite, and whether possibly they represent a richer solid solution (as in phosphorous streaks) or, perhaps, even a binary or ternary constituent. The mottled appearance, however, may be due to the polishing. A rough mottled structure in some grains results from hurried polishing in the final stages and is a quite common occurrence. A somewhat different sort of mottled surface may also be obtained because of prolonged polishing. Figure 24 (*a*) shows the mottled appearance (lighter colored patches) produced in a low-carbon steel by long polishing with magnesia in the final stage. A strong impression may be gained that the patches represent another constituent than ferrite or that they are at least appreciably different from the rest of the ferrite. After deeper etching, however, as in Figure 24 (*b*), it seems clear that the mottled patches are not some other constituent but are the result of the covering over by the final polishing of series of intersecting scratches in the ferrite. Under the microscope the connection between the mottled appearance and polishing scratches is well brought out by changing focus. The mottled appearance in ferrite is found not only in abnormal steel, but in normal steel as well. Figure 24 (*c*) and (*d*) shows the mottled appearance of the ferrite in a normal and abnormal specimen. At the bureau, repeated attempts by polishing and etching to reveal any consistent difference in the appearance of the ferrite between normal and abnormal steel have been without result. The "eutectoid" has not been detected

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[37] G. F. Comstock, "Discussion of abnormal steels," Trans. Am. Soc. Steel Treat., 12, p. 415; 1927.

either in the carburized layer or in the core of specially prepared high-oxygen iron.[38] Despite the many workers on this problem, no one has been able to show a difference between normal and abnormal steel by means of the copper-bearing etching reagents, such as Stead's, Le Chatelier's, etc. These reagents ought to be very sensitive in revealing the "iron-carbon-oxygen eutectoid," if it exists. It seems justifiable to conclude that the "eutectoid," of itself, and as an explanation of abnormality, is still unproved.

6. INCLUSIONS

In surveys of the inclusions in normal and abnormal steel it was usually possible to detect more alumina inclusions in the abnormal specimens. No very definite relation was found, however, between abnormality and the total number of inclusions. It should be noted that a characteristic of the structure of the carburized layer of abnormal steel is its uniformity; even though variations and segregations of abnormality are frequent, in general, the abnormal features extend very uniformly. It is true that near decided segregations of oxide inclusions the abnormality often becomes most pronounced, but scattered individual inclusions do not seem to exert any noticeable influence on the normality of the surrounding structure. This is one of the reasons why it has been considered that the oxides responsible for abnormality are present not as ordinary sized inclusions but as submicroscopic inclusions which are assumed to be very evenly distributed. From the term "submicroscopic" it is evident that such inclusions can not be detected under the microscope. Normal and abnormal steel specimens carefully polished were examined at high magnification for the very smallest inclusions that can be distinguished to see if there is any difference between normal and abnormal steel in the number of these particles, but no differences were found.

In X-ray diffraction patterns[39] of specimens of commercial normal and abnormal carburizing steels similar in chemical composition the positions of the bands coincided exactly in the two types of steel. The bands in the pattern of the normal steel were somewhat more discontinuous, an indication that it had a coarser grain than the abnormal steel. The only pattern obtained in each case was of the steel; no signs whatever of the pattern of the inclusions can be obtained by this method. It has been reported[40] that abnormal steel specimens showed a greater lattice parameter than normal steel specimens. This conclusion has been questioned,[41] however, on the

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[38] C. H. Herty, jr., J. M. Gaines, B. M. Larsen, W. A. Simpkins, The Physical Chemistry of Steel Making: The Solubility of Iron Oxide in Iron, Bulletin 34, 1928. Mining and Metallurgical Investigations, Carnegie Institute of Technology.

[39] Frederick Sillers, jr., junior metallurgist, Bureau of Standards.

[40] O. E. Harder, L. J. Weber, and T. E. Jerabek (see footnote 9, p. 430).

[41] See footnote 9, p. 430; discussion of paper by Frederick Sillers, jr.

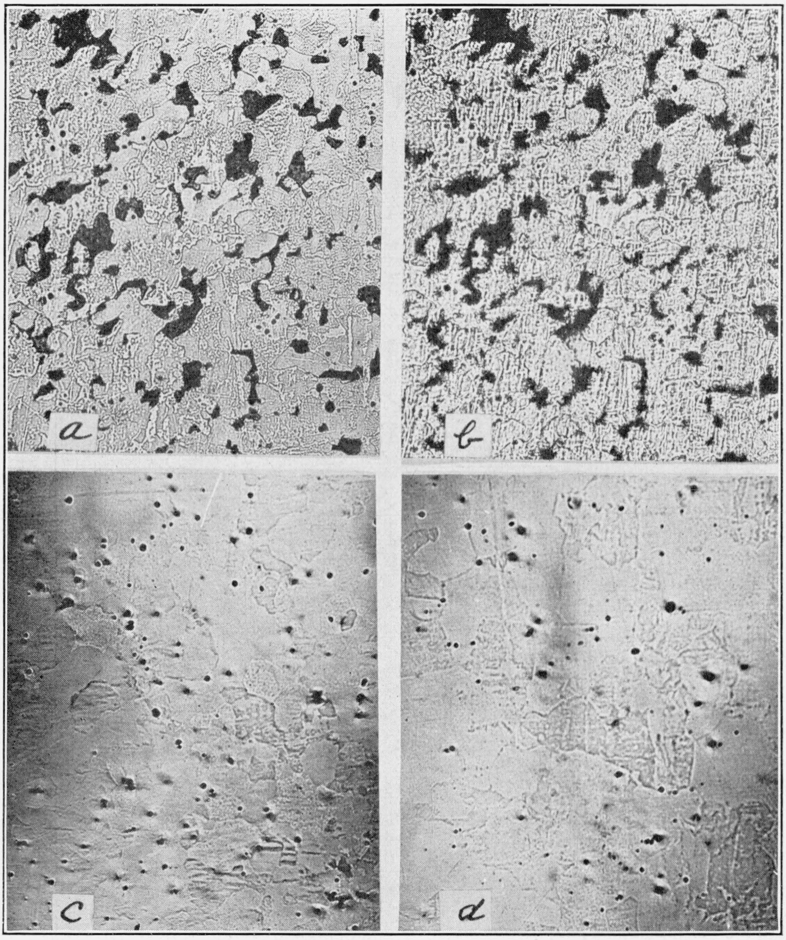

FIG. 24.—*Mottled appearance of ferrite due to polishing.* × *100*

a, after long polishing with magnesia; slightly etched with 5 per cent picric acid in alcohol; the mottled appearance is very marked; *b*, same spot as *a*, more deeply etched. This micrograph suggests very strongly that the mottled appearance is due to scratches; *c*, not etched; mottled appearance after prolonged polishing with magnesia of a normal steel specimen; *d*, not etched; mottled appearance after prolonged polishing with magnesia of an abnormal steel specimen. The mottled structure in *c* and *d* was made more evident by "stopping down" the iris diaphragm

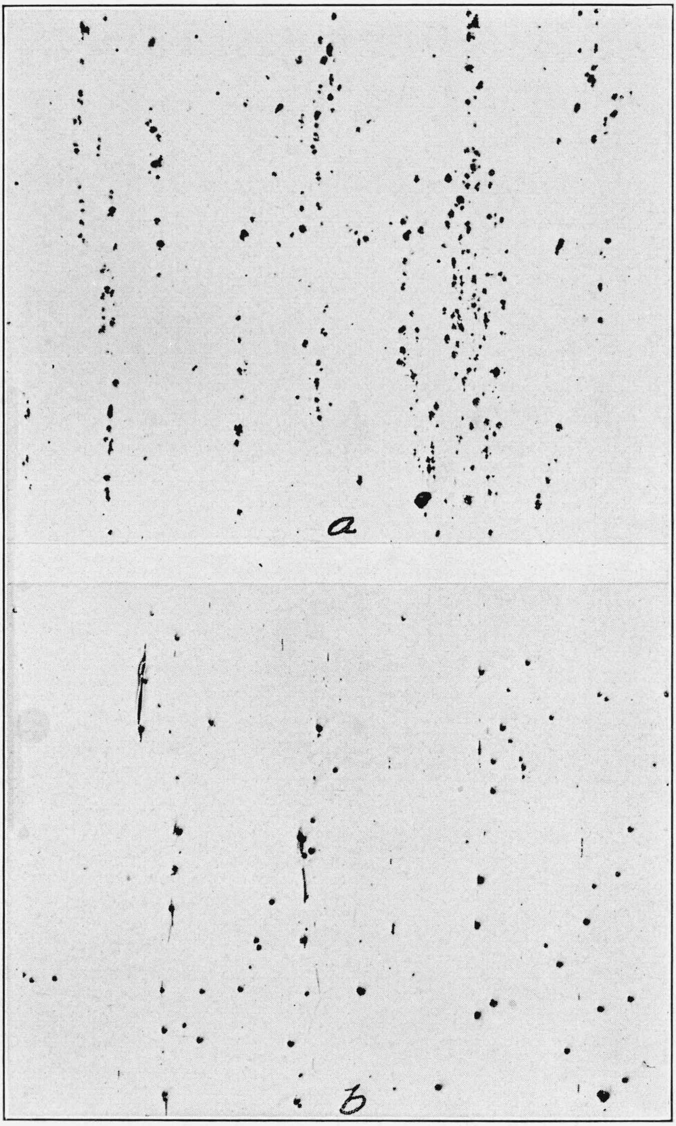

FIG. 25.—*Inclusions in commercial, normal, and abnormal carburizing steel.* × *100*

a, abnormal steel; *b*, normal steel

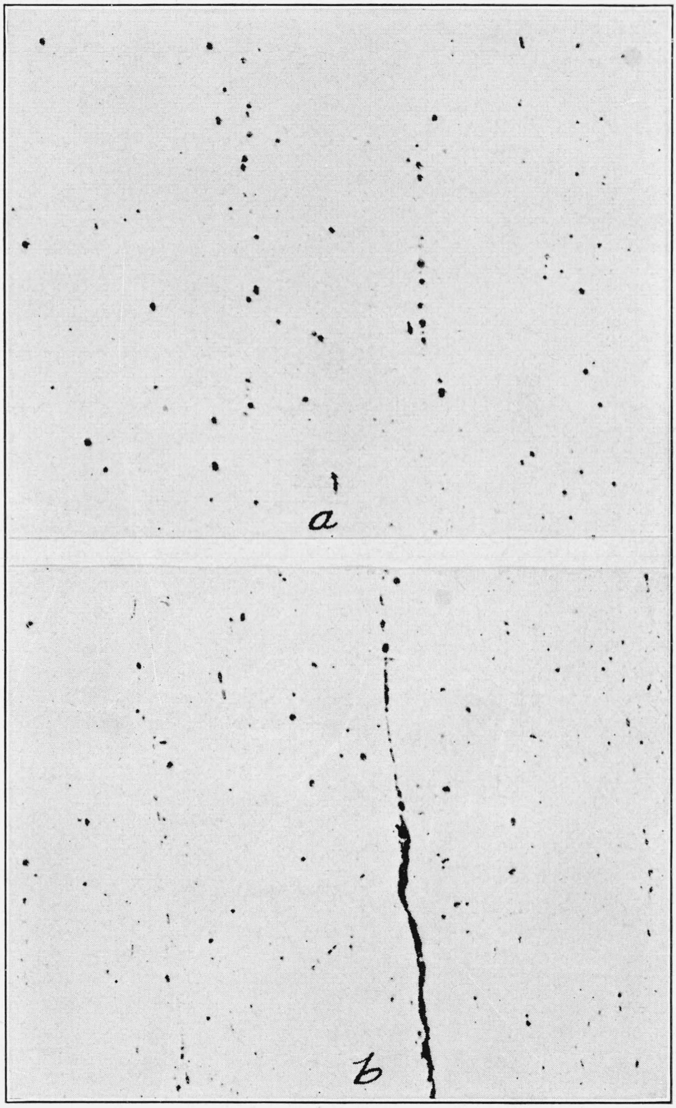

FIG. 26.—*Inclusions in commercial, normal, and abnormal carburizing steel.* × *100*

a, abnormal steel; *b*, normal steel

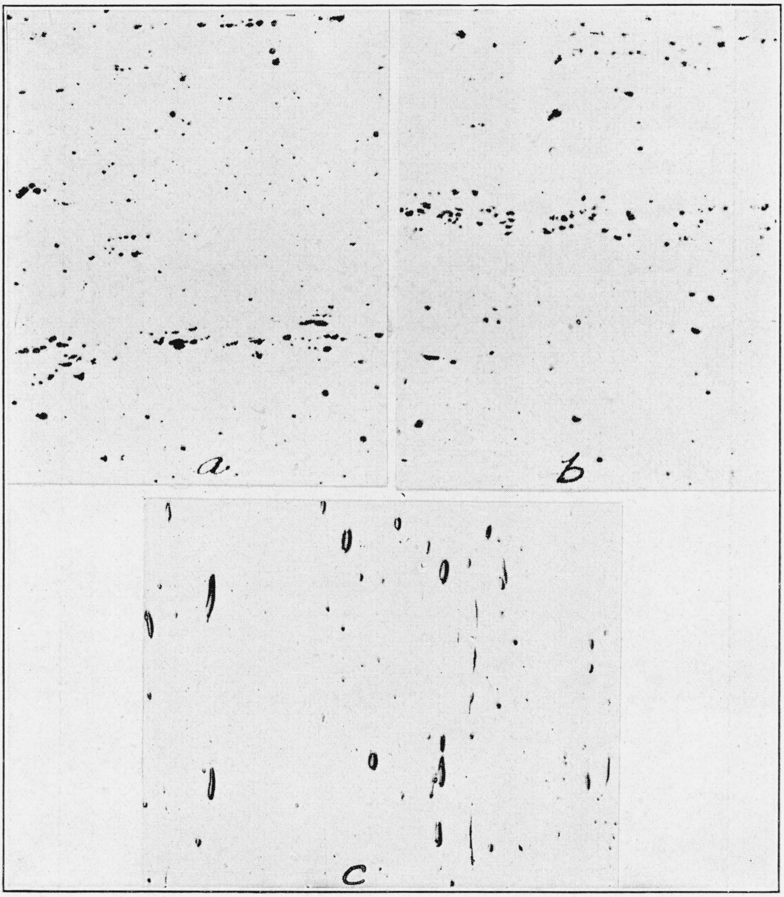

FIG. 27.—*Inclusions in commercial, normal, and abnormal carburizing steel.* × *100*

a, abnormal steel; *b*, normal steel; *c*, special manganese carburizing steel

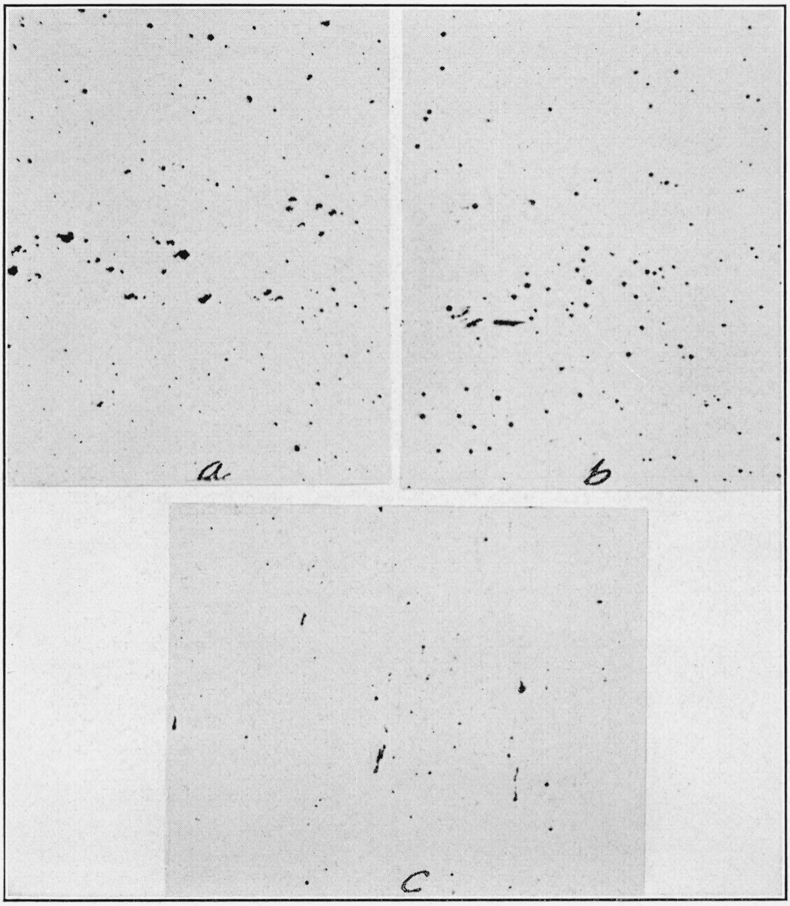

FIG. 28.—*Inclusions in specially treated steel; heat 1, 0.11 to 0.14 per cent carbon killed steel.* × *100*

a, treated with 4 pounds aluminum in the mold; abnormal; *b*, treated with 25 pounds 37 per cent ferrovanadium in the mold; abnormal; *c*, regular untreated ingot from same heat; normal

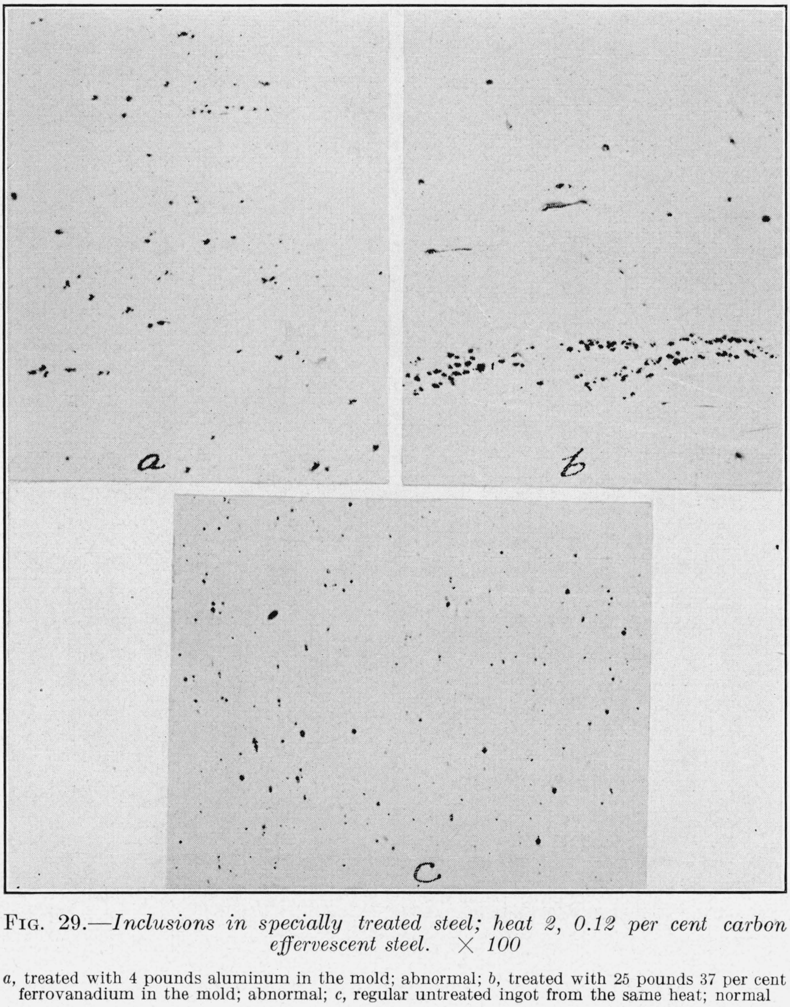

FIG. 29.—*Inclusions in specially treated steel; heat 2, 0.12 per cent carbon effervescent steel.* × *100*

a, treated with 4 pounds aluminum in the mold; abnormal; *b*, treated with 25 pounds 37 per cent ferrovanadium in the mold; abnormal; *c*, regular untreated ingot from the same heat; normal

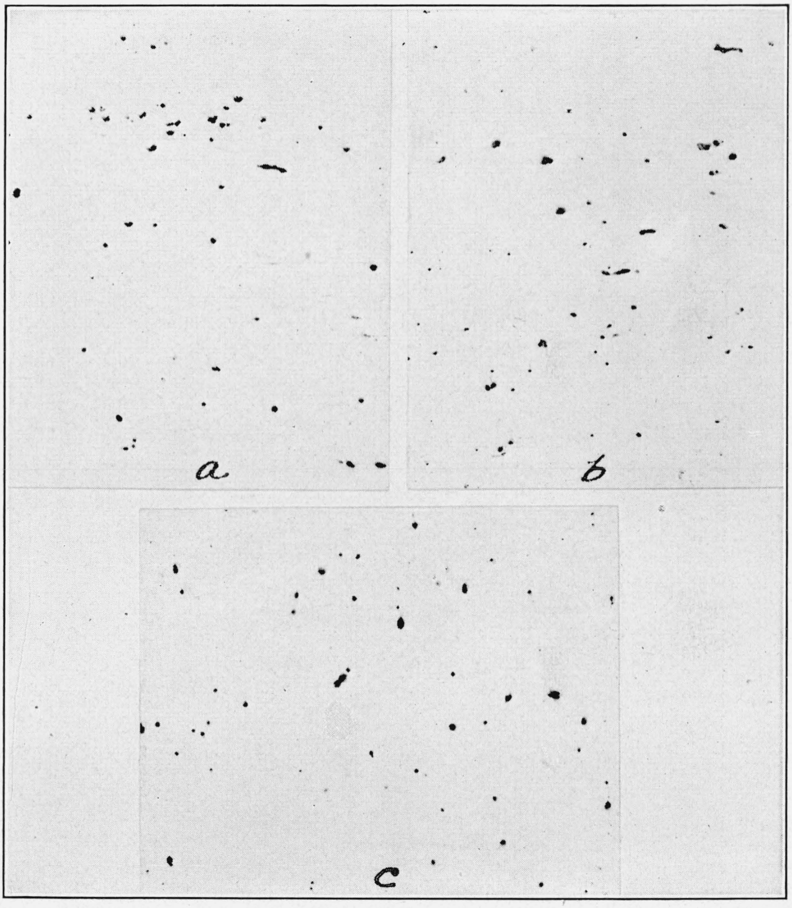

FIG. 30.—*Inclusions in specially treated steel; heat 3, 0.12 per cent carbon effervescent steel.* × *100*

a, treated with 5 pounds of aluminum in the mold; abnormal; *b*, treated with 25 pounds of 37 per cent ferrovanadium and 1½ pounds of aluminum in the mold; abnormal; *c*, regular untreated ingot from the same heat; normal

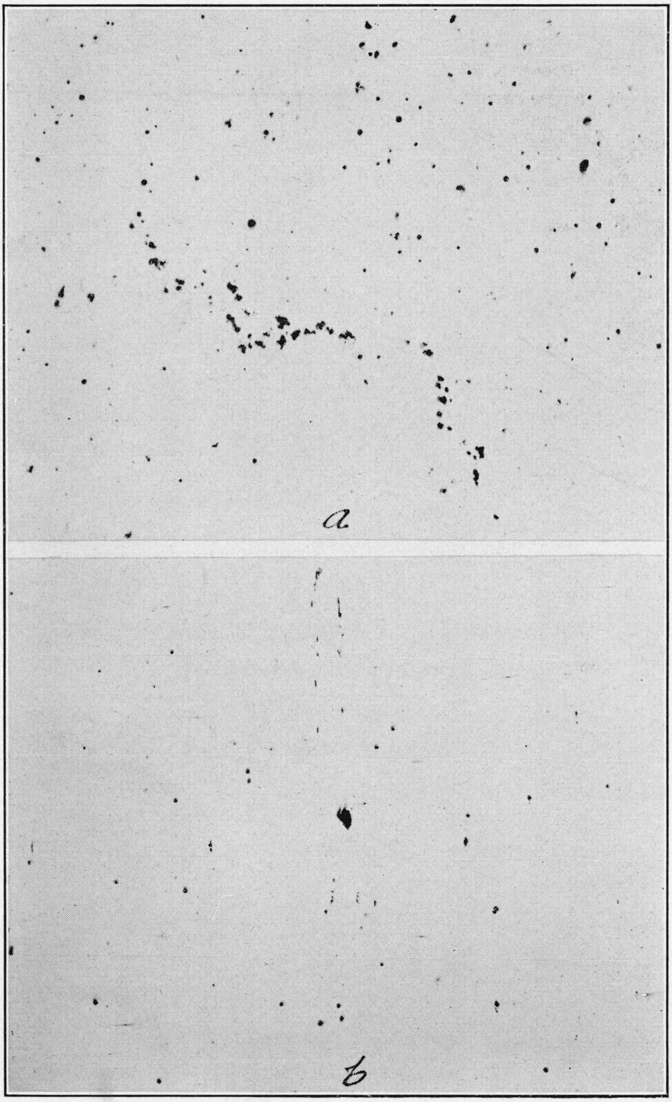

FIG. 31.—*Inclusions in specially treated steel; heat 4, 0.13 to 0.16 per cent carbon, one-half per cent nickel killed steel.* × *100*

a, treated with 25 pounds of 37 per cent ferrovanadium in the mold; abnormal; *b*, regular untreated ingot from same heat; normal ground that the observed "spread" of the diffraction bands may have been due to distortion of the crystals produced in preparing the specimen in powdered form, or to differences in chemical composition of the specimens used.

Analyses were made by the Dickenson [42] method of the oxide residues of the first six specimens of Table 14. The results are given in Table 15. They are of general interest in connection with the causes of abnormality, although they do not appear to throw any new light on the problem.

TABLE 15.—*Oxide residues by the Dickenson method* [1] *of successive ingots of killed and effervescent steel treated in the mold with aluminum or ferrovanadium, or untreated*

[The specimens are the same as the first six in Table 14 and are numbered according to their order in Table 14]

Specimen No.	Total residue	Al_2O_3	SiO_2	FeO	MnO
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*
1	0.032	0.022	0.001	0.009	(2)
2	.007	.003	.002	.002	(2)
3	.008	.002	.002	.003	<0.001
4	.028	.017	.001	.010	.001
5	.034	<.001	.010	.011	.01
6	.01	<.001	.001	.008	(2)
	Percentage composition of the total residues				
1	0.032	68	3	29	---------
2	.007	34	31	30	---------
3	.008	21	22	42	6
4	.028	60	3	35	---------
5	.034	<4	28	32	28
6	.01	<10	7	75	---------

[1] Analyses by H. A. Bright, associate chemist, Bureau of Standards.

[2] Not detected.

Although the ordinary-sized inclusions may not have a direct bearing on the cause of abnormality, it is still of interest to show representative micrographs of the number of inclusions in normal and abnormal steel. Figures 25, 26, and 27 show the inclusions in representative specimens of commercial normal and abnormal steels. In these micrographs the abnormal specimens can usually, although not always, be recognized by the presence of alumina inclusions. Often, however, normal specimens also contain alumina inclusions. The total number of inclusions in a normal and abnormal specimen may be very nearly the same. An excessive number of alumina inclusions generally indicates abnormal steel. It should be noted (fig. 27) that the special manganese carburizing steel (of high sulphur content), which was normal, contained a large number of inclusions. The presence of manganese sulphide inclusions appears to have no effect whatever on the degree of normality; specimens of screw stock con-

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[42] J. H. S. Dickenson, "A note on the distribution of silicates in steel ingots," Iron & Steel Inst., **103**, p. 177; 1926.

taining a large number of these inclusions had perfectly normal structures. Figures 28, 29, 30, and 31 show the inclusions in the steels of Table 12 deoxidized with aluminum or ferrovanadium. The steels treated with aluminum or ferrovanadium in the mold generally, although not always, showed more inclusions than the regular untreated steel from the same heats.

In Figure 29 the number of visible inclusions in the steel treated with aluminum and ferrovanadium in the mold does not seem to be greater than the number in the regular steel from the same heat, although the treated ingot of this heat seemed to be just as abnormal as the treated ingots of the other heats. Such evidence appears to be in line with the supposition of McQuaid and Ehn that abnormality is mainly due to submicroscopic inclusions, presumably oxides. As already stated, such inclusions are not revealed by the microscope or by the X-ray spectograph. Various methods of chemical analysis, in which nonmetallic residues are obtained after solution of the steel in some reagent, may be considered as a means of detecting the presence of such inclusions, but the question at once arises whether or not a reagent which has little or no solvent action on a large nonmetallic inclusion of a given composition will be similarly inert when the inclusion is of colloidal dimensions. In any method involving filtrations it is uncertain that all or any of the finely divided material will be retained by the filter. In decantation losses may arise through the failure of colloidal-sized particles to settle. Ignition of the residue is likely to change the state of oxidation of oxides of metals with two or more valencies.

Unless some new method or research tool becomes available, it appears that our understanding of the causes of abnormality must continue to rest on circumstantial evidence. The method of attack which should give most information of direct use in the control of normality appears to be that of synthesis rather than analysis; that is, work along the general lines of the deoxidation experiments made in the cooperative work at the Central Alloy Steel Corporation's plant. By the choice of raw materials and the control of furnace operation, slag composition, and the time and method of adding deoxidizers, several steel plants have the matter sufficiently under control so that they feel able to produce at will steel of a predetermined degree of normality and abnormality. Comprehensive laboratory work along these lines, in which the different variables may be kept under better control than in commercial furnaces, is in progress in the Bureau of Mines laboratories in Pittsburgh. Work on the solubility of various oxides in liquid and solid steel at different temperatures, the chemical action of different slags, the composition of the inclusions formed under different conditions, the rate of reaction when different deoxidizers are added to the steel in various stages of the "finishing" process, and on the gravity elimination of inclusions may be expected to throw light on this problem. When the relation of these factors to abnormality are studied, the cause and control of abnormality will no doubt be better understood, but even then the evidence would still be circumstantial. However, the slip-interference theory of hardening by precipitation and agglomeration to a critical submicroscopic size of particles of metallic compounds, which so satisfactorily explains the age-hardening of duralumin, likewise rests upon evidence which is essentially circumstantial, and yet that fact has been no bar to the general acceptance of the theory.

In regard to the mechanism of formation of the abnormal structure, it is evident that, in the absence of any data as to the state in which the oxides presumed to be the cause of abnormality are present, nothing very definite can be said. The fact that the abnormal microstructure possesses two distinct, although related, features—namely, fine grain and coalescence of the cementite—would suggest that the cause of abnormality may be of a duplex nature. Thus, it is, perhaps, possible that the fine grain is due to relatively larger oxide particles (the behavior of foreign particles in obstructing grain growth is, of course, well recognized), whereas the coalescence of the cementite is due to finer particles, or perhaps to dissolved oxides. From the deoxidation tests with aluminum and ferrovanadium (VI, 2) we may, perhaps, infer that the bulk of the material causing abnormality is in a fine state of distribution rather than in solution, since it is rather improbable that aluminum oxide is in true solution in the steel.

7. THERMAL ANALYSES

Differences between normal and abnormal steel have been brought out by thermal analyses [43] (inverse-rate curves) made in the modified Rosenhain furnace in use at the bureau. The differences appeared in the cooling curves of uncarburized samples, but not in the heating curves; they did not appear when the samples were carburized, probably because the modification in the heat effect produced by abnormality is obscured in the presence of high carbon content. It was thought at first that thermal analysis might possibly be used as a supplementary method for detecting abnormal steel, but this idea had to be given up, since the differences in the curves between normal and abnormal steel are rather slight and are readily obscured by differences in chemical composition. The significant features of the thermal analysis curves are best illustrated by a series of cooling curves of the steels of Table 12 treated with aluminum or ferrovanadium in the mold, shown in Figure 32. The same features were brought out in thermal analyses of a number of samples of commercial normal and abnormal steel.

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[43] W. A. Tucker, assistant scientific aid, Bureau of Standards.

As may be seen in Figure 32, the Ar_1 transformation in the abnormal specimen of each heat occurred at a slightly higher temperature than that of the corresponding normal steel. The Ar_1 transformation was also sharper; that is, it occurred more nearly at one temperature, and the maximum time of arrest at the Ar_1 point was greater in the abnormal than in the normal steels. Thus, in heat 1, in the aluminum-treated steel, the maximum time of arrest at Ar_1 was 21 seconds; in the regular ingot it was 14 seconds. As can be seen in Figure 32, in the rest of the heats there was a corresponding difference between the normal and abnormal steels in the maximum time of arrest at Ar_1.

A possible interpretation of the above-mentioned characteristics of the cooling curves of abnormal steel is that they are a reflection of the same conditions as produce coalescence and separation of the cementite from the ferrite in the carburized layer of abnormal steel. The fact that the Ar_1 point occurs at a higher temperature and more sharply at a single temperature in abnormal than in normal steel would indicate that the cementite forms more readily when the Ar_1 temperature is reached in abnormal than in normal steel. This is the probable reason why abnormal steel is more prone to give soft spots. Cementite forms more readily in abnormal steel, and so, on quenching, troostite is more readily produced and a faster cooling rate is required to retain martensite. Harder[44] has given a discussion of the mechanism of formation of the abnormal structure in the carburized layer, based largely on deductions from the microstructure, that in abnormal steel cementite is less soluble in the austenite and has represented this by lines on the iron-carbon equilibrium diagram. It is very doubtful, however, whether the existing experimental data justify such a representation. The thermal analyses made in this work indicated that, upon heating, the cementite of abnormal steel goes into solution at the same rate as in normal steel, the heating curves of the two kinds of steel (uncarburized stock) being similar. The difference between the two was shown only on cooling; apparently the cementite in abnormal steel forms more abruptly, perhaps because of the presence of submicroscopic particles of oxides acting as nuclei for precipitation, as stated in Ehn's original theory.

VII. PRACTICAL ASPECTS

The problem of soft spots in casehardened articles due to the character of the steel used presents no difficulties that can not be overcome by increasing the cooling rate in quenching or by changing the type of steel used. The real question is how to deal with the problem in any particular plant. This will depend on considerations

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[44] See footnote 9, p. 430.

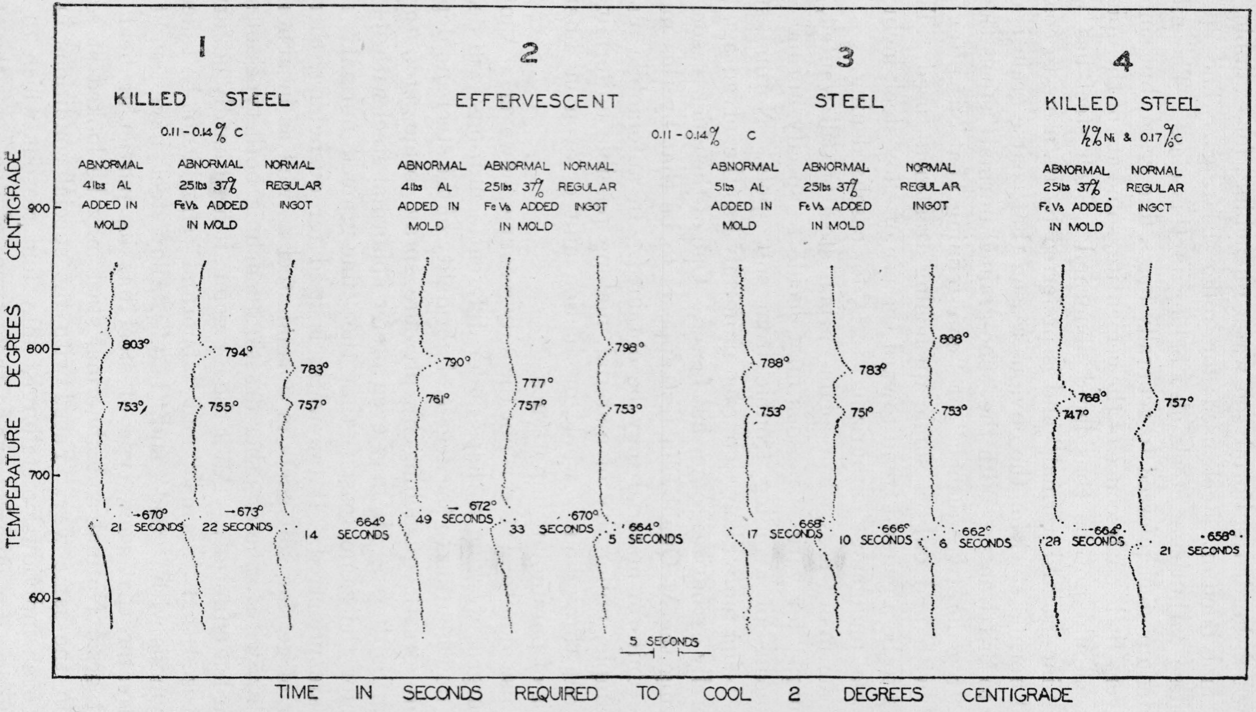

FIG. 32.—*Inverse-rate cooling curves of normal and abnormal steel*

The Ar_1 point in the abnormal specimens occurred at a slightly higher temperature and more sharply at one temperature than in the normal specimens of practice, equipment, quality, cost, and the personal preference of the metallurgist, as with any practical metallurgical problem.

One solution of the problem has been the use of the alloy carburizing steels which harden uniformly on water quenching, for example, the nickel molybdenum steel used for roller bearings. The special manganese carburizing steels also belong in this class. The nickel molybdenum steel referred to generally has a fine grain, but since it shows very little coalescence of the cementite, some are of the opinion that it should not be considered abnormal. Such steel has been called "fine-grained normal" and is preferred by its users to coarse-grained normal steel for the obvious reason that coarse grain is conducive to brittleness. With the "fine-grained normal" steels the so-called "regenerative quench" or "core-refining heat" is often dispensed with and only a single quenching treatment used. There appears to be a general trend toward the use of alloy steel, including the special manganese carburizing steels, for casehardening.

For the many uses where plain carbon steel is still wanted, the metallurgist for various reasons may decide to specify normal steel as a means of avoiding trouble from soft spots. Normal steel, besides being more likely to harden uniformly has the advantage that it generally carburizes somewhat faster. One of the chief reasons for specifying the McQuaid-Ehn test appears to be that by this means a more uniform material may be obtained. In automobile plants, for example, uniformity of material, making possible uniformity of treatment throughout a whole production unit or even in different units, is of paramount importance.

The use of normal steel is not the only recourse, however. Another metallurgist, working perhaps under different conditions, will decide to pay no attention to the degree of normality of the steel and depend on more drastic quenching by pressure spray, brine, etc., to get uniform hardness. He may even prefer abnormal steel with its fine grain, for the same reasons that the "fine-grained normal" alloy steels are preferred. If tap water is used for quenching, there is danger of getting soft spots in normal steel as well as in abnormal steel, but with brine or other drastic quenching both types of steel will harden uniformly. After the foregoing, it need hardly be further emphasized that "normal" and "abnormal" should not be taken as synonymous with "good" and "bad." Alloy steels have taught the steel treater that each type of steel has its particular field and advantages. Normal and abnormal steel may be looked at somewhat in the same way. Faced with the special conditions in his plant, each individual metallurgist may find reasons which to him are sufficient for favoring one of these types of steel over the other.

From the standpoint of the steel maker the results of the deoxidation tests described indicate that, after suitable experimentation, a steel manufacturer ought to be able to produce normal and abnormal steel at will, subject, of course, to the limitations of chemical composition. Except under very unusual circumstances, it would hardly be possible, for instance, to produce a coarse-grained vanadium steel. Fine grain would be preferable not only for carburizing steel, on account of the greater impact strength, but also for other uses, as, for instance, in sheet steel where coarse-grain size is detrimental for certain purposes. The McQuaid-Ehn test is sensitive to variations in the melting and deoxidation procedure and may become a very useful test in the hands of the steel maker for studying and controlling his product.

VIII. SUMMARY

The characteristics of the extremes of the normal and abnormal microstructure, as well as of the intermediate gradations, are described. Normal steel carburizes somewhat more deeply than abnormal steel. Segregations of abnormality may occur. Mechanical treatment seems to have no noticeable effect on the degree of normality. After certain heat treatments, especially annealing in hydrogen, abnormal steel assumes a more normal structure.

On water quenching abnormal steel is more prone to give soft spots. However, on quenching in brine or sodium hydroxide solution abnormal steel, as well as normal steel, hardens without soft spots. It was found that air or other gases ordinarily dissolved in quenching water may cause soft spots.

After carburizing, the core of carburized abnormal steel, probably because of its finer grain, shows higher impact strength than the corresponding normal steel.

High-carbon steels (tool steels) show features of normality and abnormality similar to those met in carburizing steels.

Most cases of abnormality in commercial steel seem to be associated with the use of aluminum for deoxidizing. Nothing arose during the progress of the experiments to controvert Ehn's theory that abnormality is due to dissolved oxides or, more probably, undissolved submicroscopic particles of oxides. The results of spectrographic analyses for aluminum, deoxidation tests of commercial steel with aluminum and ferrovanadium, examinations of small test ingots taken during the progress of open-hearth heats, oxygen and alumina analyses, surveys for inclusions, and thermal analyses—made in the study of the causes of abnormality—are described and discussed.

The authors take pleasure in acknowledging the hearty cooperation of the many metallurgists and steel companies who generously provided samples for the investigation, and who also gave their advice and freely divulged the results of their experience on this problem, making the study a truly cooperative one between the bureau and the industry.

It would make too extended a list to credit everyone who has shown an active interest in the work, but, in addition to those who have been mentioned in the footnotes, acknowledgment is due the following: Bureau of Mines, Crucible Steel Co., Driver Harris Co., Jones & Laughlin Co., Chrysler Corporation, Pittsburgh Crucible Steel Co., Reo Motor Co., and Timken Roller Bearing Co. The passing mention in the footnotes really does not do justice to the amount of time spent on the work at the Central Alloy Steel Corporation and the Trumbull Steel Co.; in the experiments made at the latter plant the Titanium Alloy Manufacturing Co. and the Union Carbide & Carbon Co. aided materially. E. W. Upham, of the Chrysler Corporation, was largely instrumental in the bureau undertaking the study of the problem.

WASHINGTON, May 23, 1928.

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