A STUDY OF COLD-WORKED LOW-CARBON STEEL AND AN INVESTIGATION OF TUBE FAILURE IN 1400 lb. BOILER

Thesis for the Degree of M. S.

C. L. Crandall

1937

THESIS

Steel

Title: Cold-worked low-carbon steel

Chemical engineering

A STUDY OF COLD-WORKED LOW-CARBON STEEL and AN INVESTIGATION OF TUBE FAILURE IN 1400 lb. BOILER

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I wish to thank and acknowledge my indebtedness to Professor H. Publow, Dept. of Chemical Engineering, Michigan State College, for the help and advice he so willingly gave me in the writing of this thesis.

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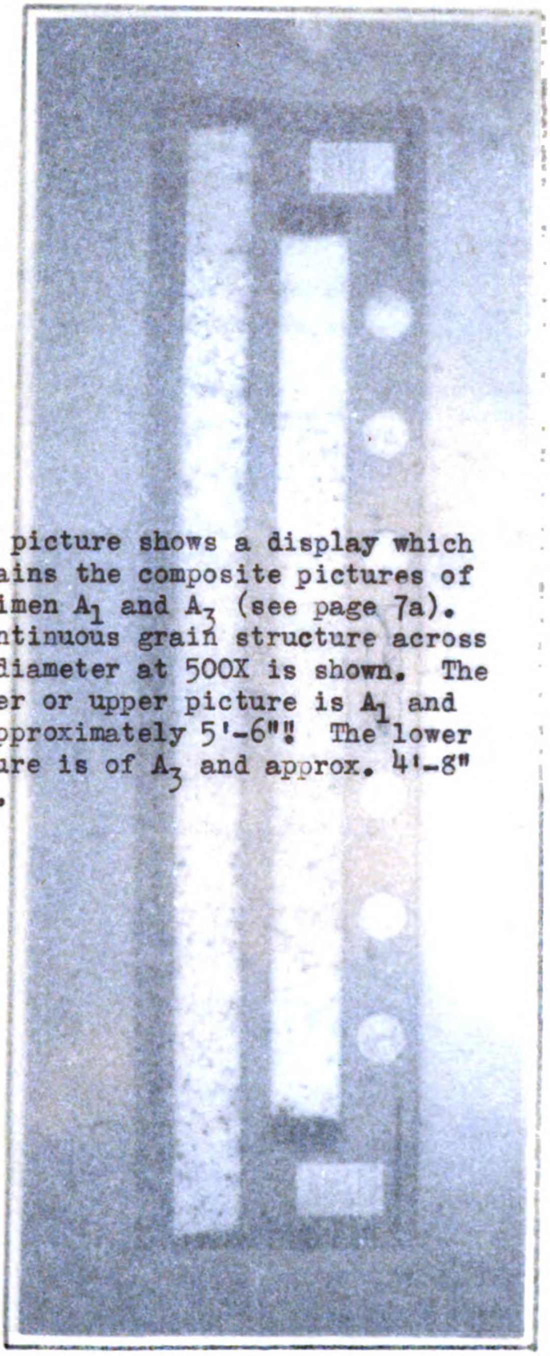
SECTION I. - A STUDY OF COLD-WORKED LOW-CARBON STEEL.

SECTION II - AN INVESTIGATION OF TUBE FAILURE IN 1400 lb. BOILER.

SECTION I.

A STUDY OF COLD-WORKED LOW-CARBON STEEL.



This picture shows a display which contains the composite pictures of Specimen A_1 and A_3 (see page 7a). A continuous grain structure across the diameter at 500X is shown. The longer or upper picture is A_1 and is approximately 5'-6"! The lower picture is of A_3 and approx. 4'-8" long.

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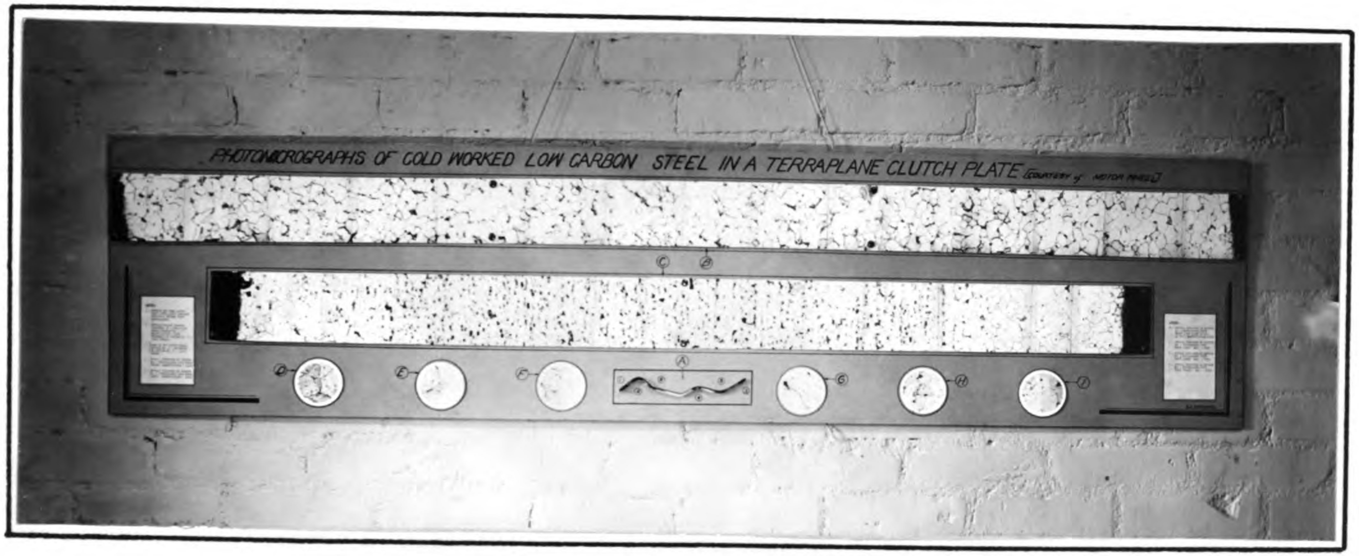

PHOTOMICROGRAPHS OF COLD WORKED LOW CARBON STEEL IN A TERRAPLANE CLUTCH PLATE

INTRODUCTION

One of the chief difficulties confronting the steel manufacturer is his endeavor to supply the steel fabricator with material which will not only meet all of the physical requirements, but also satisfactorily withstand the deformation required to produce the fabricated part. Failures are particularly noticeable where the steel must have ductility, that is, low-carbon steel. This is indeed unfortunate as the physical and mechanical properties of this type of steel has increased the volume of its use until it is now well-defined by many as the "steel of commerce."

The use of tremendous pressure upon dies to deform flat, strip steel naturally demands a certain degree of ductility. Steel of this type is usually first formed into strips by hot-rolling the original ingot. By hot-rolling is meant the working of the metal above the recrystallization range to retain certain desireable properties such as small grain size and toughness.

The particular steel under observance in these pages is what is termed "killed steel"; that is, "Molten[1] steel which has been held in the ladle, furnace, or crucible (and usually treated with Aluminum, Silica, or Manganese) until no more gas is evolved and the ladle is perfectly quiet." Figure No. 1 illustrates the effect of this "killing" of the steel is to decarburize the outer sections of the ingot. The ingot or casting is then hot-rolled in several reducing operations until the thin or strip steel is obtained. The strip steel is then subjected to cold- working at the place where the fabrication

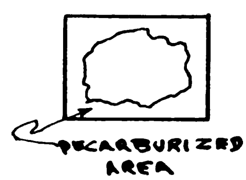


FIGURE NO. 1

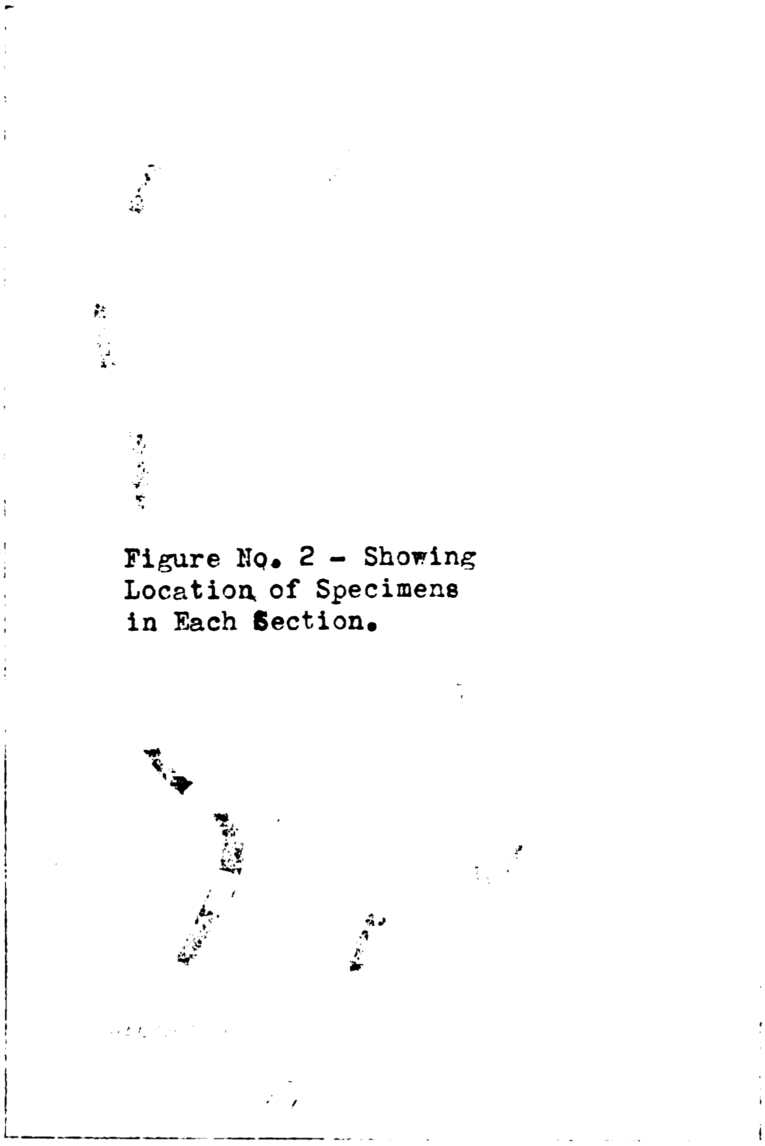


Figure No. 2 - Showing Location of Specimens in Each Section.

Figure No. 2 - Showing
Location of Specimens
in Each Section.

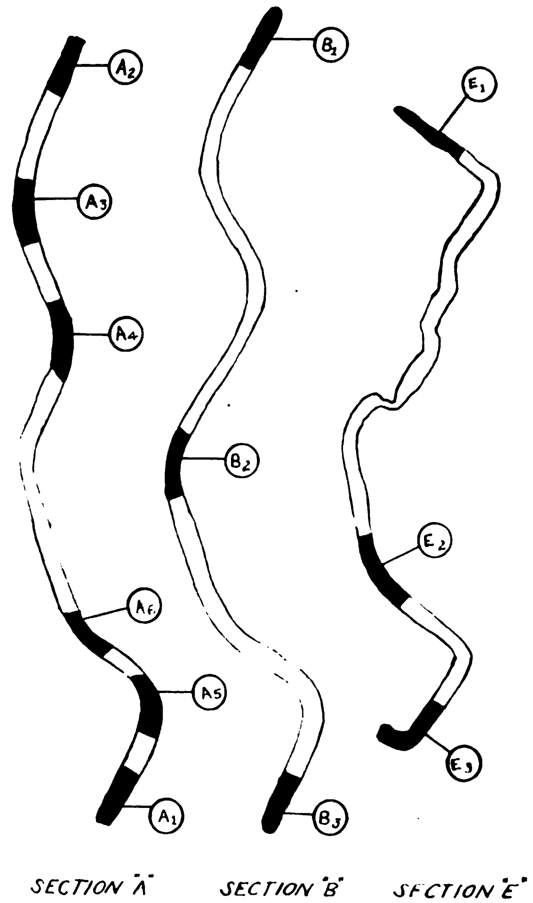


FIGURE NO. 2

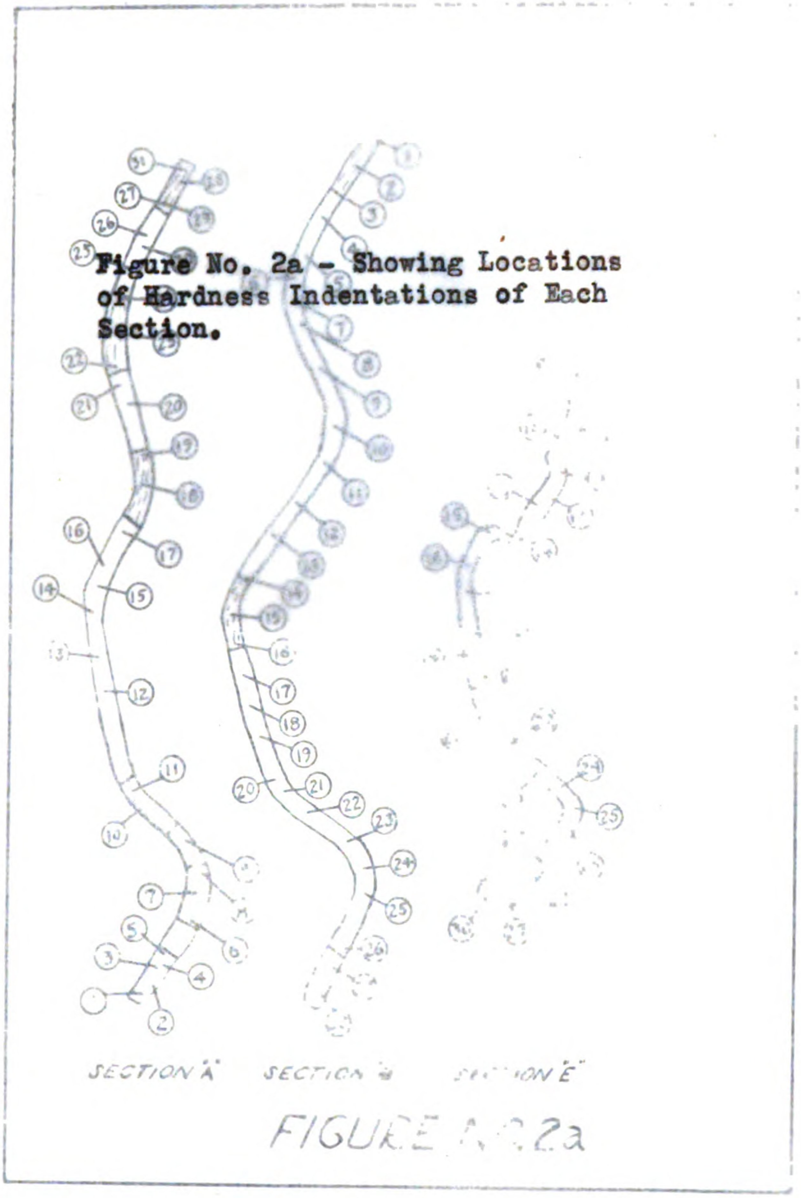
is to take place, the great force of the dies forming the shape desired.

For the metal used in the Terraplane Clutch Plate made by the Motor Wheel Corporation, Lansing, Michigan, the description in the above paragraphs adequately pictures the preliminary steps in its manufacture. However, there are five distinct pressing operations whereby the strip metal is progressively shaped into the final or finished product. It has often been the failure of a certain shipment of this steel to withstand this progressive deformation that has been the source of many tons of scrap metal and the loss of much money to both the steel manufacturer and the consumer.

It is the purpose of this paper to investigate the structure and various properties exhibited by various sections of the clutch plate after being subjected to one or more of the pressing operations. This will entail a discussion of such items as cold-working theory, plastic and elastic deformation, structure of grain boundaries, reduction of area by working, and grain movements.

The paper will be divided into three parts, viz., (1) The analysis of the various sections of the clutch plate; (2) The advancement of various theories relative to the cold-work phenomena exhibited in part one; and (3) A summary and conclusion involving cold-worked metal as found by the author.

Figure No. 2a - Showing Locations of Hardness Indentations of Each Section.



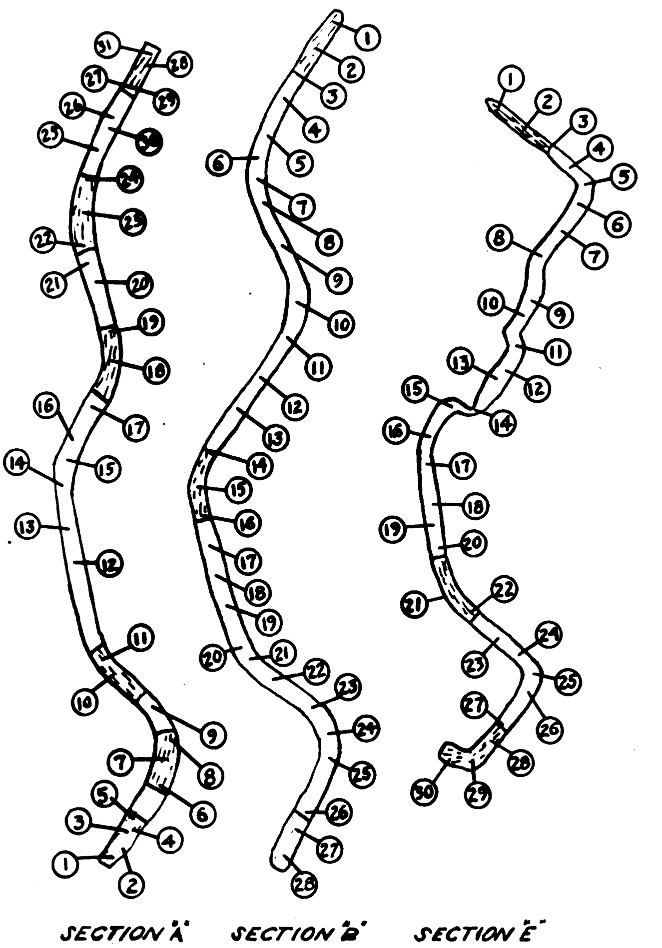


FIGURE NO. 2a

METHOD OF CUTTING SECTIONS

Sections were cut from the clutch plate as follows: Section A was cut from a plate that had undergone the first pressing operation; Section B, from one involving two pressing operations; and Section E, after all five operations had been performed, or in other words, the finished product as far as the shaping of the piece was concerned. Sketches of the three sections are shown in Figure No. 2, giving the actual sizes and shapes of each from a cross-sectional view. Each section will be discussed separately. It is to be understood that each section is in itself a different piece of metal, and not the same piece at different stages of pressing. There will also be found, at the end of this section, tables showing the data collected, and an index to the photomicrographs shown.

SECTION "A"

This section was shown to be a "killed steel", with the carbon seemingly concentrated in the center of the specimens of A_2, A_3, A_4, and A_6,(for location of specimens in section, see Figure No. 2) with the edges composed of larger ferrite grains which have little or no pearlite intermingled with them. That is, the outer edge of each specimen has been decarburized due to the "killing" of the steel. "Ghost lines"[2] are in evidence in the specimens named above, the photomicrographs of those depicting the typical structure of the center portion of the strip of metal. "Ghost lines are long bands of ferrite grains in the direction of the working", and in which the carbon has seemingly been pushed to one side to give a white line effect due to the ferrite grains.

The phenomena of Specimen A_1 and Specimen A_5 being uniform in grain size through out can be well explained in Figure No. 3. With Figure No. 1 in mind, and looking along the plane EDFG, it can be seen that the carbon would be more

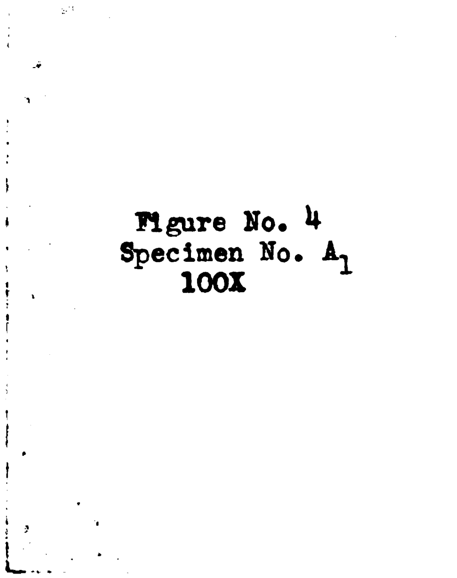


Figure No. 4
Specimen No. A_1
100X

Figure No. 5
Specimen No. A_2
(center). 100X

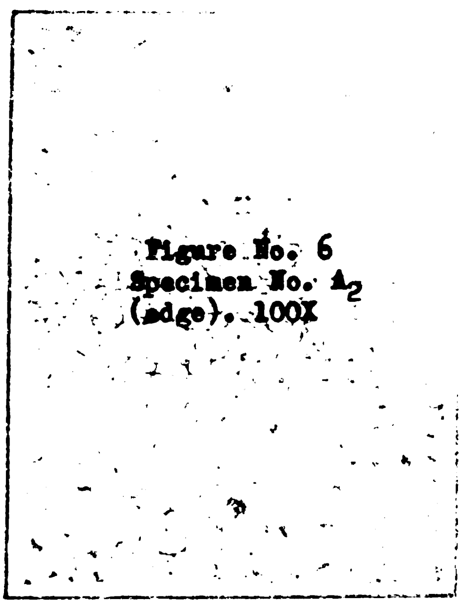


Figure No. 6
Specimen No. A_2
(edge). 100X

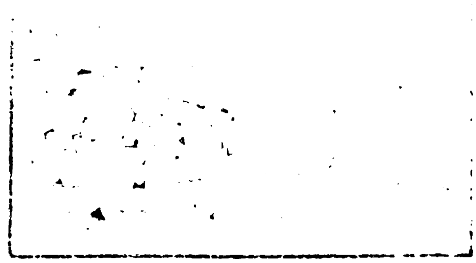


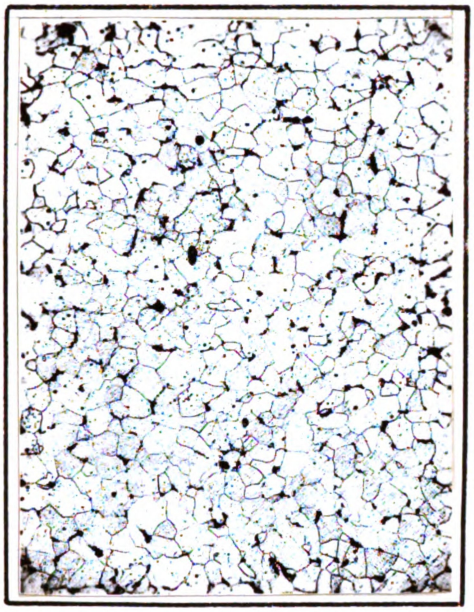
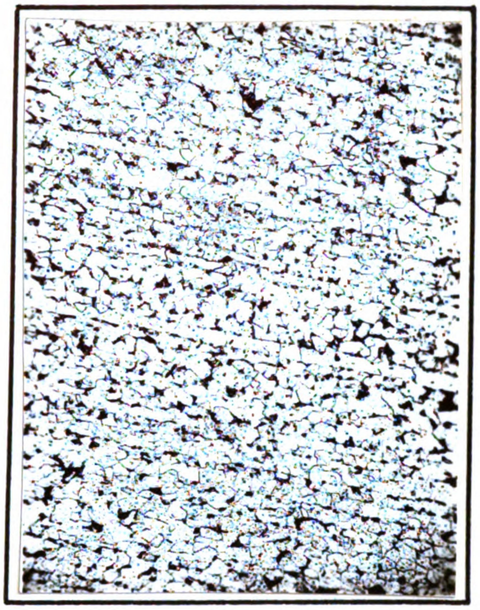
Figure No. 7
Specimen No. A_3
(edge). 100X.

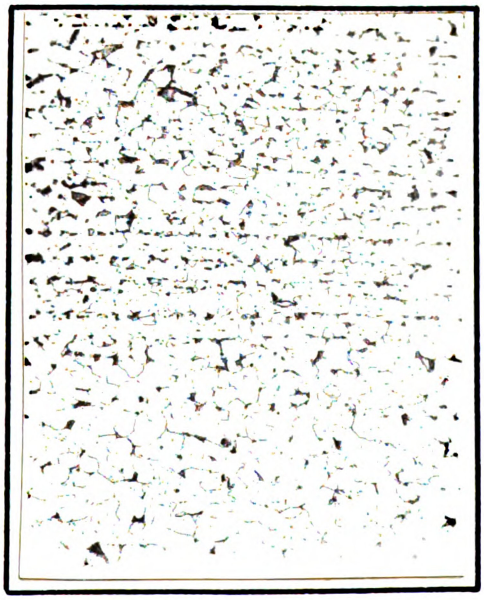
Figure No. 4
Specimen No. A_1
100X

Figure No. 5
Specimen No. A_2
(center). 100X

Figure No. 6
Specimen No. A_2
(edge). 100X

Figure No. 7
Specimen No. A_3
(edge). 100X



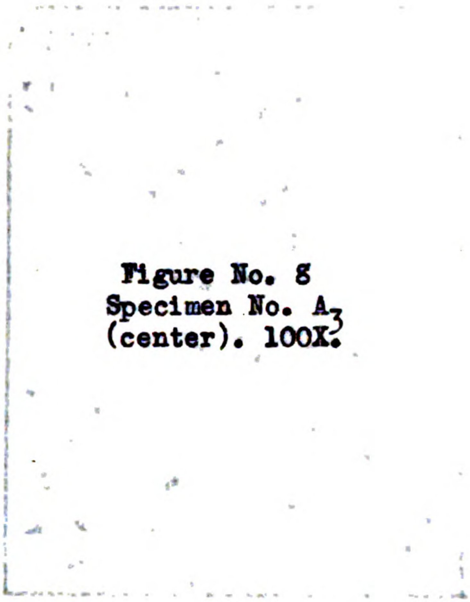


Figure No. 8
Specimen No. A_3
(center). 100X.

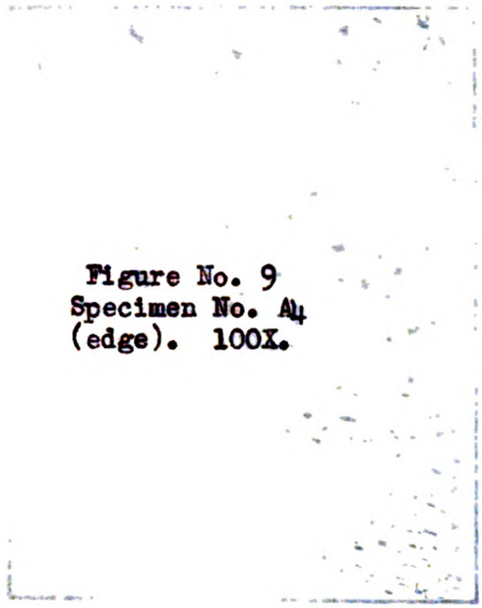


Figure No. 9
Specimen No. A_4
(edge). 100X.

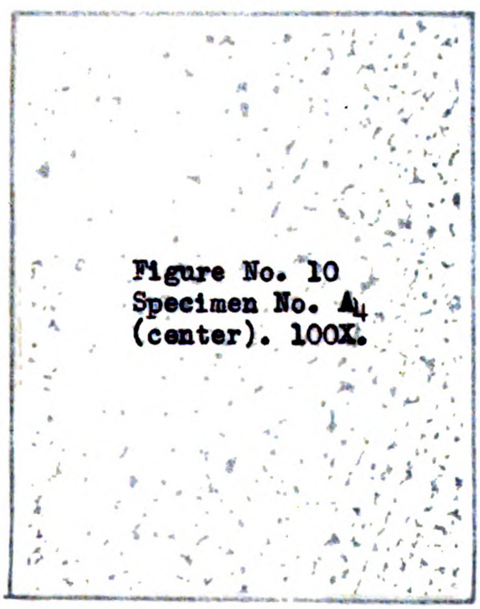


Figure No. 10
Specimen No. A_4
(center). 100X.

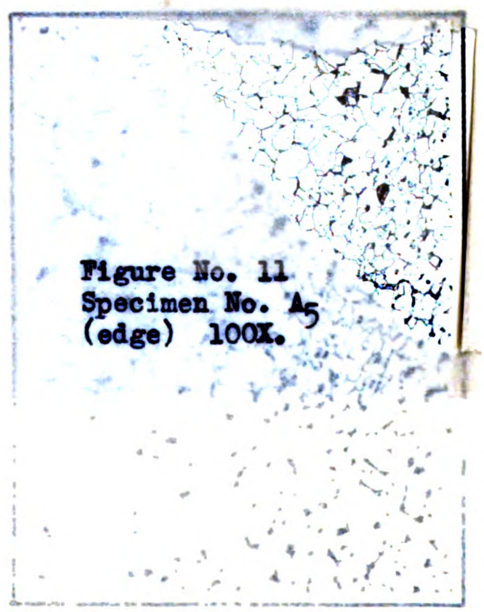


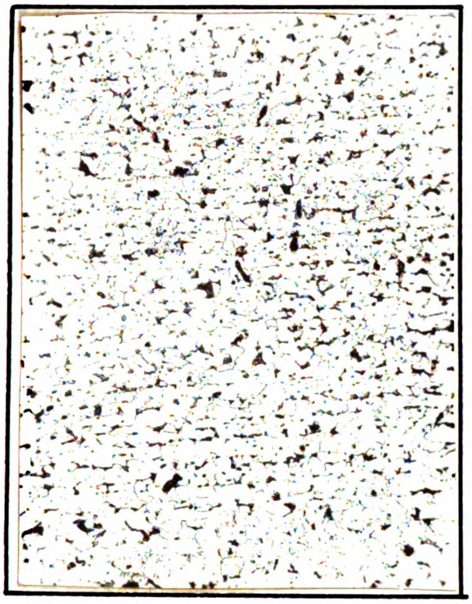
Figure No. 11
Specimen No. A_5
(edge) 100X.

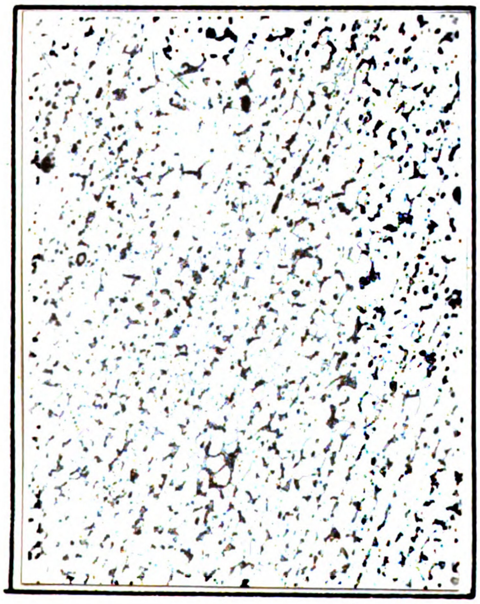
Figure No. 8
Specimen No. A_3
(center). 100X.

Figure No. 9
Specimen No. A_4
(edge). 100X.

Figure No. 10
Specimen No. A_4
(center). 100X.

Figure No. 11
Specimen No. A_5
(edge) 100X.





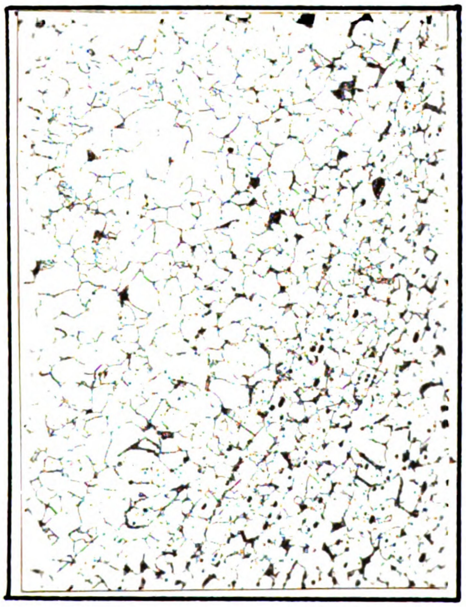
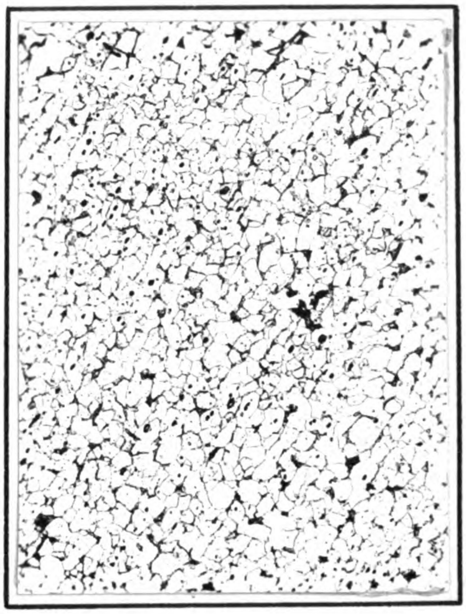


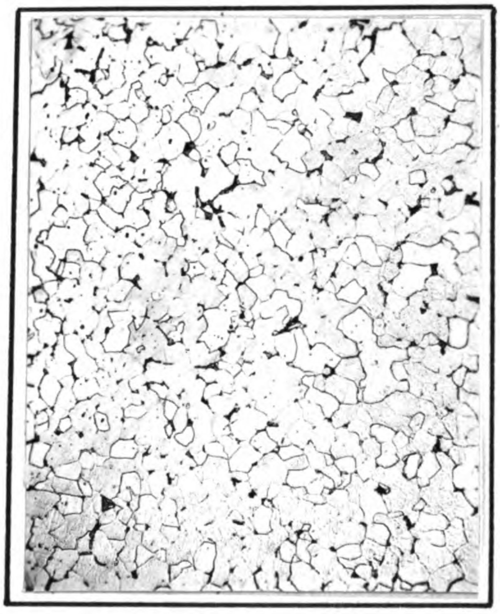
Figure No. 12
Specimen No. A5
(center). 100X.

Figure No. 13
Specimen No. A6
(center). 100X

Figure No. 12
Specimen No. A_5
(center). 100X.

Figure No. 13
Specimen No. A_6
(center). 100X





concentrated in the encircled area. With the plane EDFG representing the cross-sectional view of the section before being pressed into the form exhibited in Figure No. 2, it can be seen that a certain portion of this section will have the edges decarburized and the center containing carbon to a much greater degree, while the portion on the one end would tend to be somewhat decarburized throughout the entire cross-section. With specimen A_1 appearing at the decarburized area and specimen A_3 further down the plane, the latter would thus exhibit a decarburized area only on the two narrow edges. Thus specimen A_1 would tend to have uniform grain size throughout, due to the uniformity of structure exhibited.

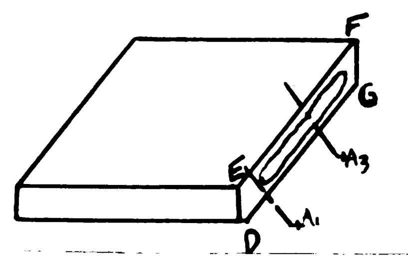


FIGURE NO. 3

Photomicrographs were taken at 100X, 250X, 500X, and 1000X. Figures No. 4 to 13 inclusive are photomicrographs taken at 100X, in which the essentials outlined above are clearly exhibited. Figures No. 4 and No. 13 clearly exhibit the uniform structure typical of Specimens A_1 and A_5.

The photomicrographs at 250X, Figures No. 14 to 19, inclusive, were taken to get the average shape of the grains. The grains were found to be polyhedral and undistorted.

In the pictures of higher magnification for this section, white strips appeared in many instances in the junctions of grain boundaries, sometimes near pearlite grains, but not necessarily so. Cementite is supposed to have the chemical formula Fe_3C, the hardest iron compound in steel. Sometimes, the white strip of cementite would completely encircle a pearlite grain, this

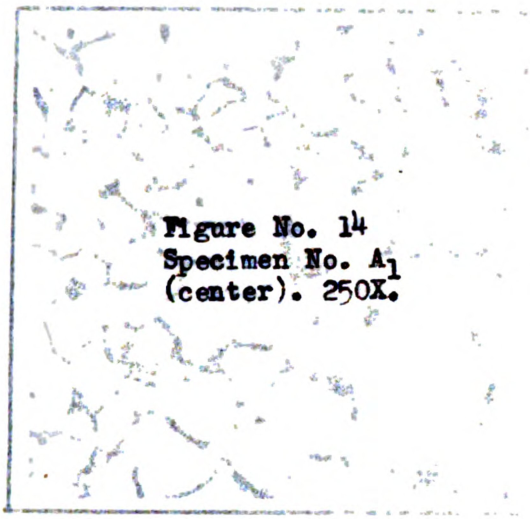


Figure No. 14
Specimen No. A_1
(center). 250X.

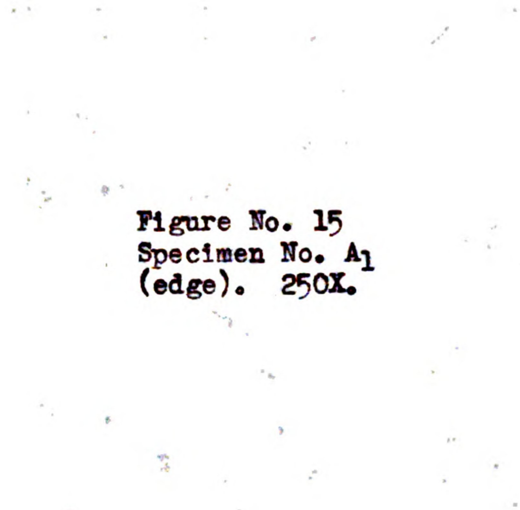


Figure No. 15
Specimen No. A_1
(edge). 250X.

Figure No. 16
Specimen No. A_4
(center). 250X.

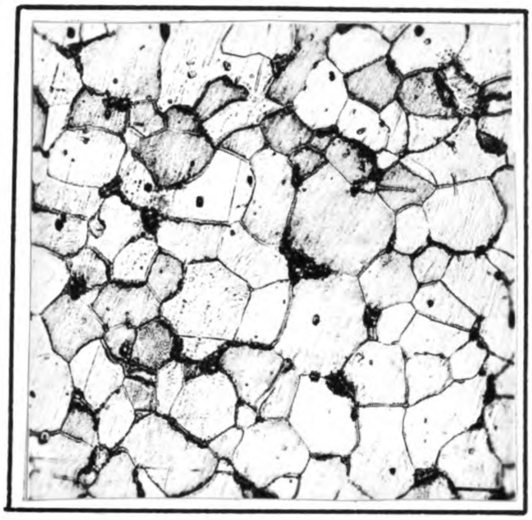
Figure No. 17
Specimen No. A_4
(edge). 250X.

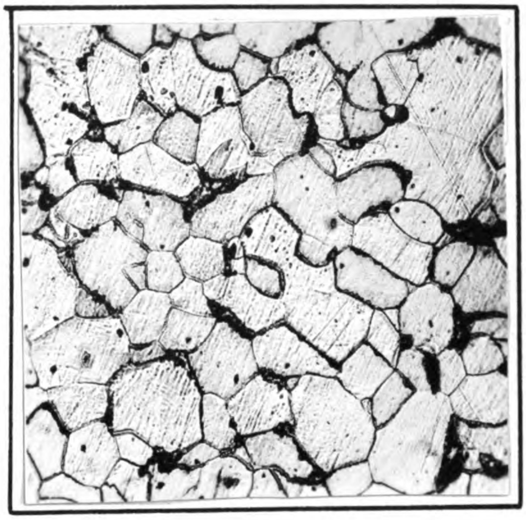
Figure No. 14
Specimen No. A_1
(center). 250X.

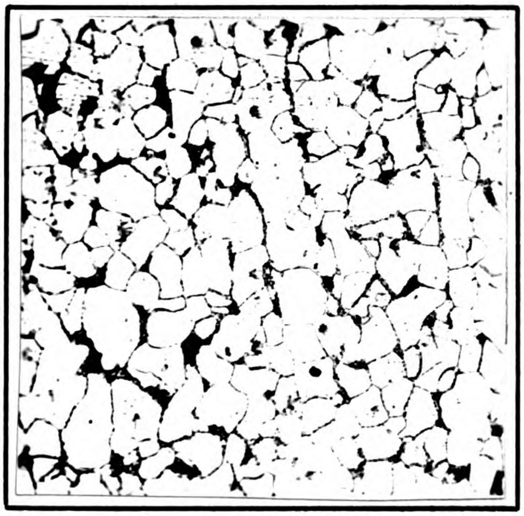
Figure No. 15
Specimen No. A_1
(edge). 250X.

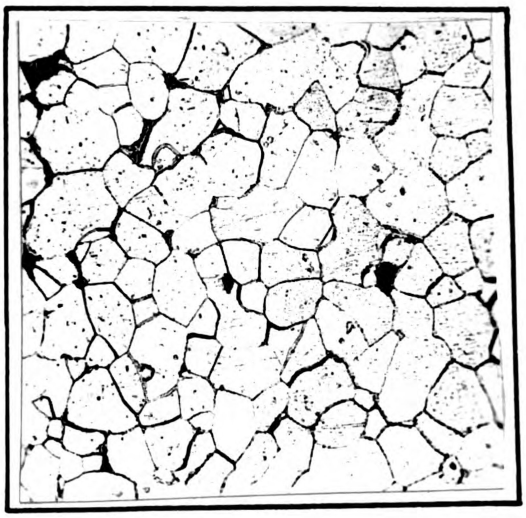
Figure No. 16
Specimen No. A_4
(center). 250X.

Figure No. 17
Specimen No. A_4
(edge). 250X.









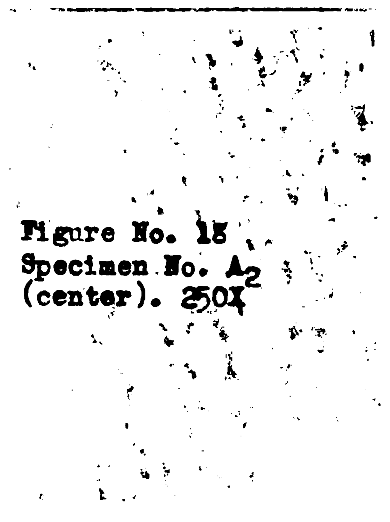


Figure No. 18
Specimen No. A_2
(center). 250X

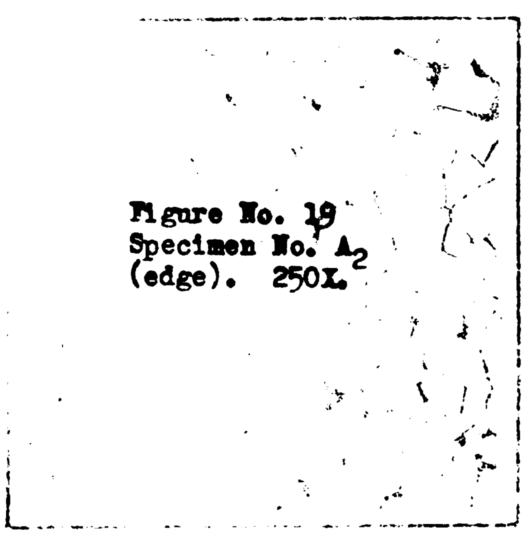
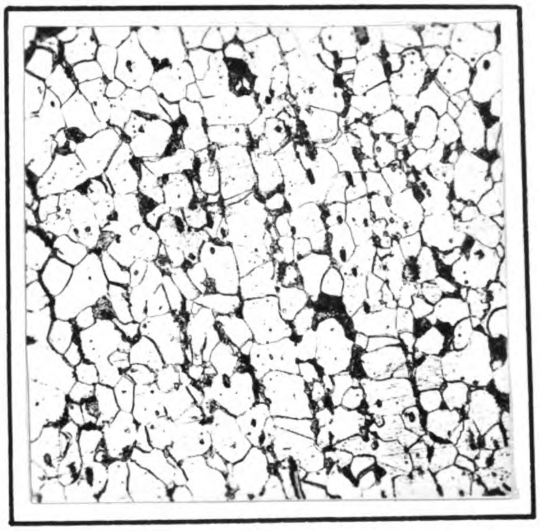


Figure No. 19
Specimen No. A_2
(edge). 250X.

Figure No. 18
Specimen No. A_2
(center). 250X

Figure No. 19
Specimen No. A_2
(edge). 250X.



being known as "divorced" cementite. When etching a specimen of steel, the solution will attack or "eat-out" all the constituents to a marked degree except cementite, which remains unnattacked. Thus the ferrite grains will be at a lower plane than the cementite. If, when focusing upon a strip of what appears to be cementite, by moving the objective nearer the specimen on the stage, the white strip comes into focus as a dark line, then sufficient evidence has been advanced that the white space is due to a deeper etching at this point. Therefore cementite is not present, but ferrite or some other metal or inclusion. But supposing on the other hand that by moving the objective away from the specimen the effect is to make the black line come into focus. This is sufficient proof that cementite is present. This condition was found to be true in several instances when viewing Section A under a high powered microscope. Photomicrographs No. 20 to 27, inclusive, exhibit possible cementite inclusion in grain boundaries and around pearlitic areas. The location of these areas are clearly defined upon the tissue used to identify each figure.

Since the steel in question is low-carbon steel, (.05 to .10% carbon), and is normally thought to be an aggregate of Pearlite and Ferrite, plus various impurities, it is necessary to explain the presence of cementite, that is, free cementite. By free cementite is meant in this instance, cementite other than that combined with ferrite to form pearlite. Figure No. 28 is a portion of the iron-carbon diagram necessary for the interpretation of this phenomena.

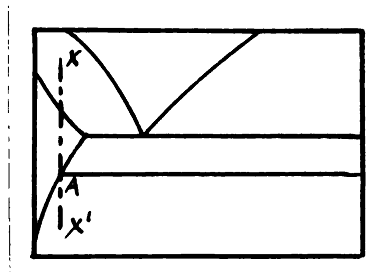


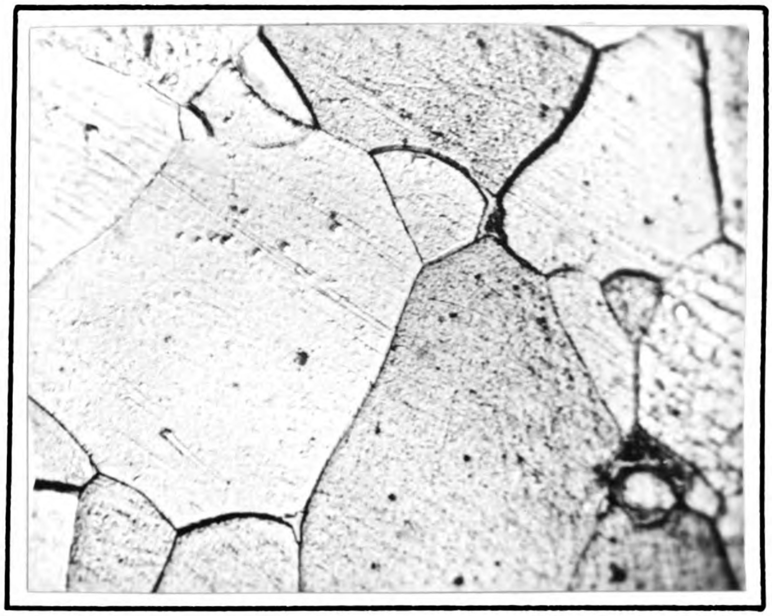
FIGURE NO. 28

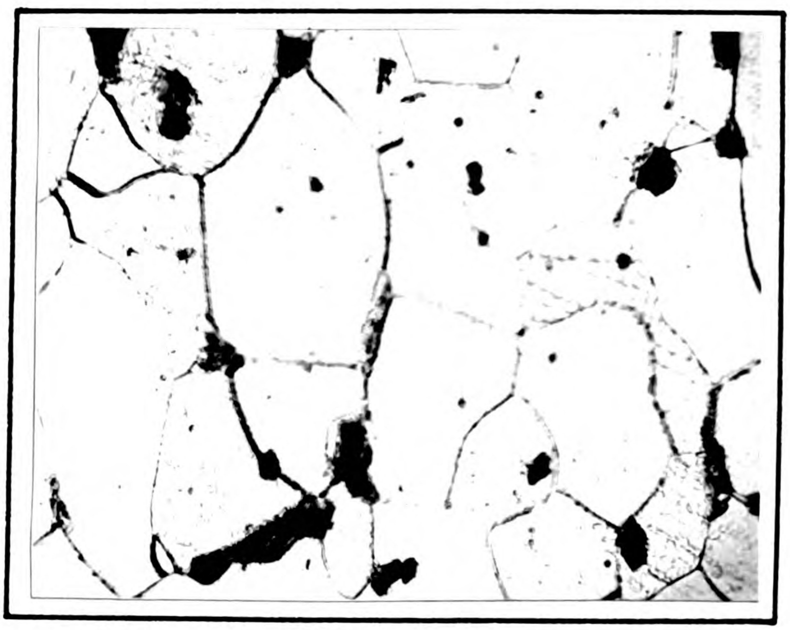
Figure No. 20. Specimen No. A_2 (edge). 1000X. Large grain in center apparently fractured. White strip in grain boundary in lower central portion. Other white strips present in grain boundaries.

Figure No. 21. Specimen No. A_2 (center). 1000X. Long grain at left apparently fractured. Also grain in upper left hand corner. Distortion and cementite present.

Figure No. 20. Specimen No. A_2 (edge). 1000X. Large grain in center apparently fractured. White strip in grain boundary in lower central portion. Other white strips present in grain boundaries.

Figure No. 21. Specimen No. A_2 (center). 1000X. Long grain at left apparently fractured. Also grain in upper left hand corner. Distortion and cementite present.





As the low-carbon steel, XX' cools, individual ferrite grains or a solid solution of alpha iron plus carbon crystallizes. If any of these ferrite grains contain less than .06% carbon, then at the point A, cementite is precipitated out.

By means of micrometer measurements, the average diameter of each specimen was obtained, that is the cross-sectional distance of each narrow strip. These diameters are indicated in Table No.1. Specimen A_1 measured .1323 inches, while at the other end of the section, A_2 measured .1126 inches, or a reduction in cross-sectional area of 15%. Next, the average number of grains were counted across the diameter of the specimen at four different places, and the average number thus determined. This was accomplished by placing the specimen under the microscope and passing it across the field of view.

The average count of grains across A_1 was found to be 123. Specimen A_2 at the opposite end of the section has been shown to be reduced in area by 15%. Therefore, if there has not been a formation of new grains produced in some manner by the cold working, and if there has been no deformation or elongation in the direction of the working, then the grains across the diameter of Specimen A_2 should be:

$$\frac{123}{1} : \frac{X}{.85} \quad \text{or } 104.5 \text{ grains.}$$

This may be shown by means of the sketch in Figure No. 29:

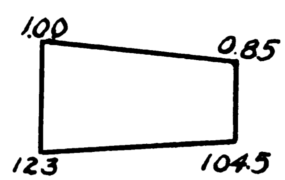


FIGURE NO. 29.

However, from Table No. 1, the average count across A_2 was 167 grains. Therefore, since there was no evidence of distortion in Figures No. 14 to 19, and since these were typical structures of the specimens, then there must have been a movement of the grains or crystals of metal accompanied by a formation of new grains, possibly caused by a breaking up of the larger grains into several smaller ones. Photomicrographs Nos 21 and 22 seem to indicate that some of the larger grains have been broken up. With the bending or stretching of the metal by the tremendous pressure of the dies, it would seem that elongation might take place before fragmentation of the crystalline structure which is supposedly quite ductile.

From Table No. 1 can be seen that in the other specimens of Section A, there has been approximately the same reduction in average grain size for correspondingly less reduction in area than the 15% experienced in Specimen A_2. Therefore, for this section, the grain size reduction has been independent of the extent of reduction of area to with 5 or 10%.

Pertinent questions involving the phenomena above are now listed. By what force or mechanism should the grains break down or new grains be produced as the steel is reduced in area? The entire specimen or section was cold-worked at room temperature and therefore there could be no recrystallization of ferrite or pearlite grains. Cold work is supposed to elongate or distort the grains, yet there was no evidence of this phenomena in Section A. What prevented the elongation or distortion of this ductile metal so strenously cold-worked at room temperature? Also the question of hardness which is supposed to accompany reduction in area in cold working; has it exhibited itself in this section? Cold-working is supposed to decrease ductility and increase hardness. Therefore, the hardness of specimen A_1 would seem to be less than for A_2 or A_3.

If there is a movement of grains in this cold-working, then how can the grains move to exhibit the characteristics exhibited in part (a) of Figure No. 30 rather than in part (b).

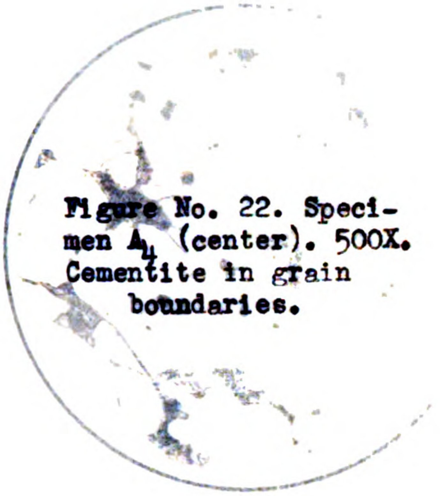


Figure No. 22. Specimen A_4 (center). 500X. Cementite in grain boundaries.

Figure No. 23. Specimen A_1. 1000X. Divorced cementite around pearlite grain.

Figure No. 24. Specimen A_1. 1000X. Ultra Violet Light Source.

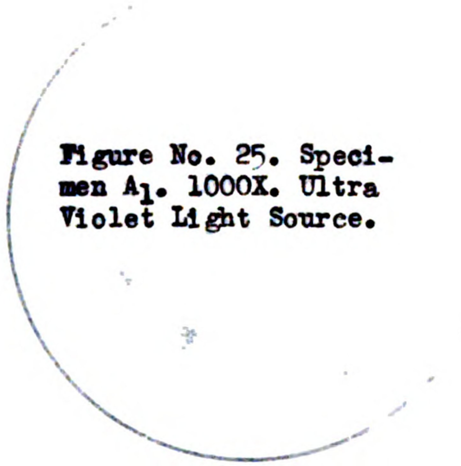


Figure No. 25. Specimen A_1. 1000X. Ultra Violet Light Source.

Figure No. 26. Specimen A_1. 1000X. White strips in grain boundaries.

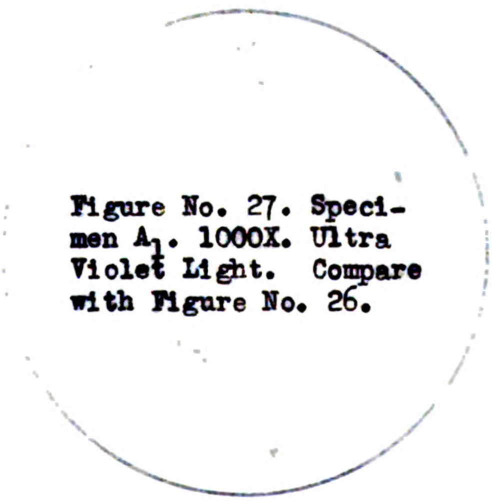


Figure No. 27. Specimen A_1. 1000X. Ultra Violet Light. Compare with Figure No. 26.

Figure No. 22. Specimen A_1 (center). 500X. Cementite in grain boundaries.

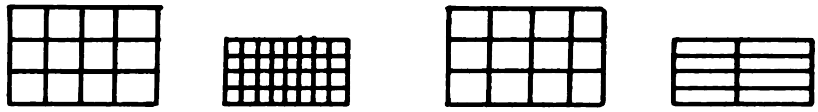
Figure No. 23. Specimen A_1. 1000X. Divorced cementite around pearlite grain.

Figure No. 24. Specimen A_1. 1000X. Ultra Violet Light Source.

Figure No. 25. Specimen A_1. 1000X. Ultra Violet Light Source.

Figure No. 26. Specimen A_1. 1000X. White strips in grain boundaries.

Figure No. 27. Specimen A_1. 1000X. Ultra Violet Light. Compare with Figure No. 26.



(a) (b)

FIGURE NO. 30

In figure No. 30, part (a), the larger sketch of cross sectioning represents the grains in Section A_1, while the smaller grains are shown in the smaller sketch, supposedly representing Specimen A_3. The grains are drawn in squares to sshow that in both cases they are undistorted. How did these larger grains get into this smaller size by the accompanying movement of metal and stretching involved? In part (b), the grains of Section A_3 appear smaller in diameter, but elongated in the direction of the working, as might be expected, yet not exhibited in Section A.

To better study the shape and distribution of the grains across sections or specimens A_1 and A_3, photomicrographs were taken in series completely across the diameter of each section at 500X. The resulting pictures of each section wbre then pieced together to give a continuous exhibit of granular structure, each composite picture when pieced together being about four inches wide and better than five feet in length. From table No. 2, it will be seen that the number of grains were counted for sections 12 inches in from the end of each picture, and the number of grains per inch times 500 determined for the distance measured. The reduction in grain size was then figured and found to be 31.2% and 23.0%, thus closely checking the results obtained in Table No. 1. There was, however, some evidences of distortion or elongation of the grains in Specimen A_3, but not to any great extent or regularity.

Table No. 5 indicates the hardness values as determined with the Rockwell Hardness Tester for Sections A,B, and E. The points upon the various sections where the readings were taken are shown in Figure No. 2a. The following items were noted concerning SectionA: (1) The hardness was greatest in the region

Figure No. 31.
Specimen No. B_1.
(center). 100X.

Figure No. 32.
Specimen No. B_1
(edge). 100X.

Figure No. 33.
Specimen No. B_2
(center). 100X.

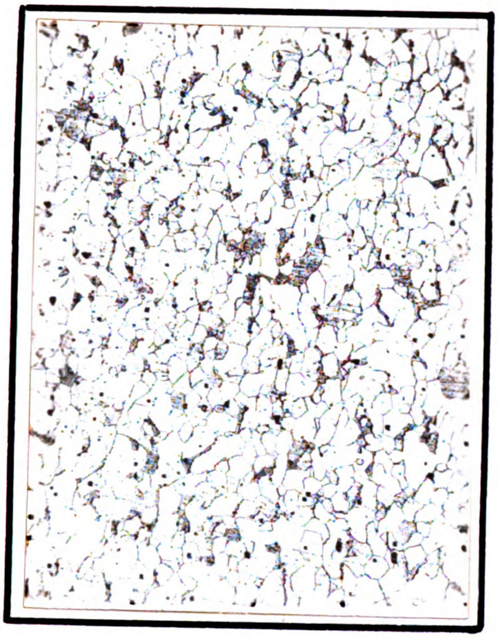
Figure No. 34.
Specimen No. B_2
(edge). 100X.

Figure No. 31.
Specimen No. B1.
(center). 100X.

Figure No. 32.
Specimen No. B1
(edge). 100X.

Figure No. 33.
Specimen No. B2
(center). 100X.

Figure No. 34.
Specimen No. B2
(edge). 100X.



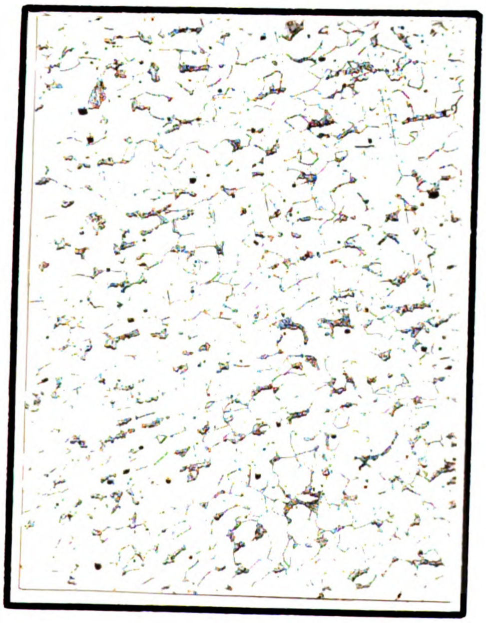
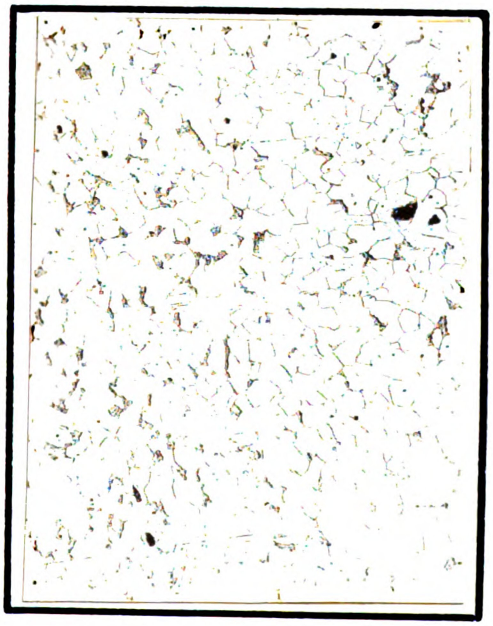



Figure No. 35.
Specimen No. B_3
(center). 100X.

Figure No. 36.
Specimen No. B_3
(edge). 100X.

Figure No. 35.
Specimen No. B_3
(center). 100X.

Figure No. 36.
Specimen No. B_3
(edge). 100X.

Figure No. 37.
Specimen No. B_1
(edge). 250X.

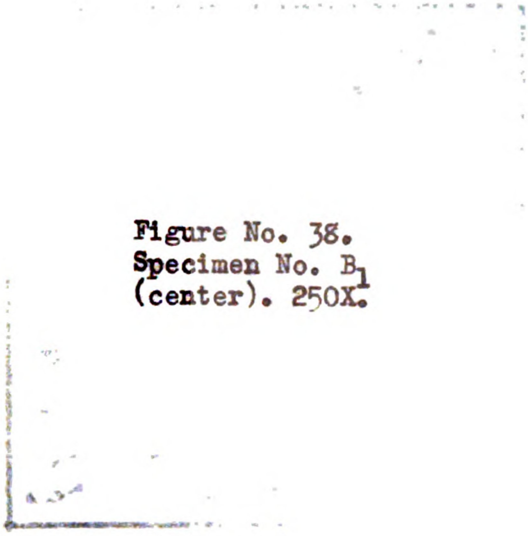


Figure No. 38.
Specimen No. B_1
(center). 250X.

Figure No. 39.
Specimen No. B_2
(edge). 250X.

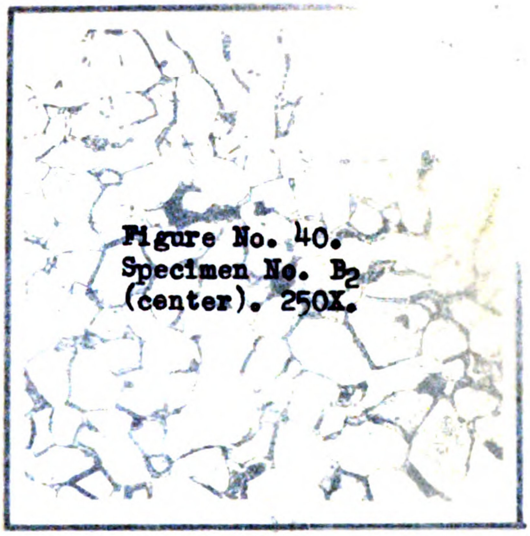


Figure No. 40.
Specimen No. B_2
(center). 250X.

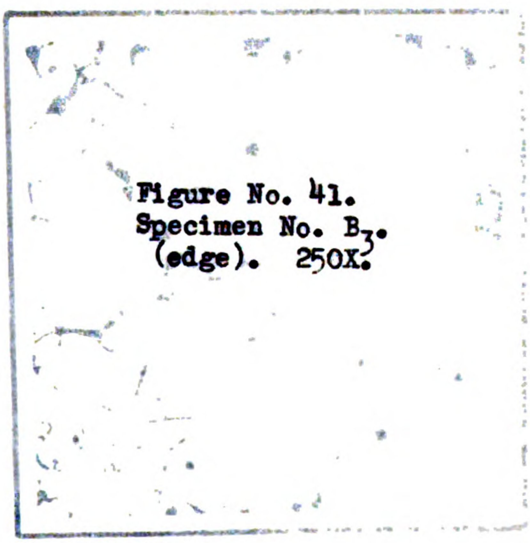


Figure No. 41.
Specimen No. B_3.
(edge). 250X.

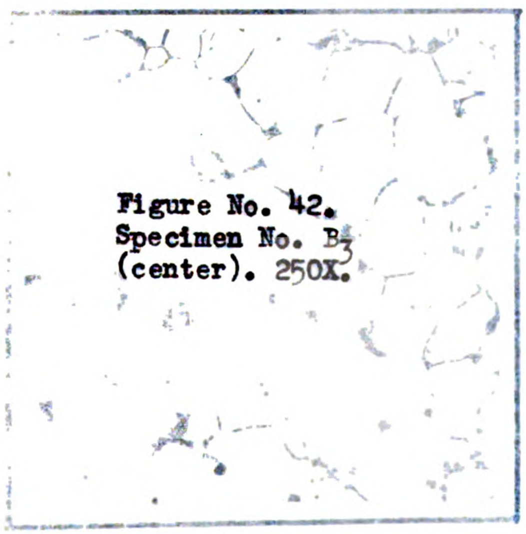


Figure No. 42.
Specimen No. B_3
(center). 250X.

Figure No. 37.
Specimen No. B_1
(edge). 250X.

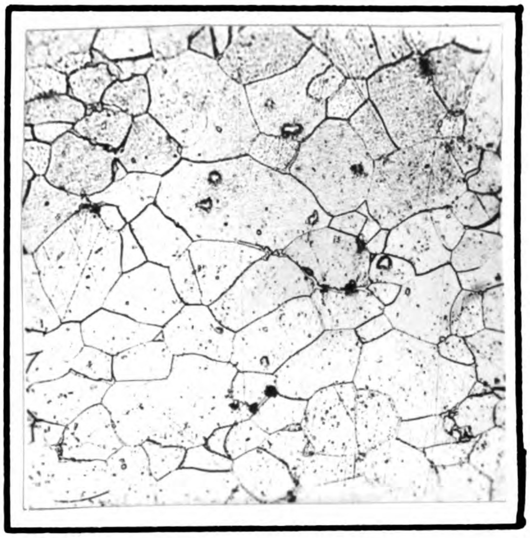
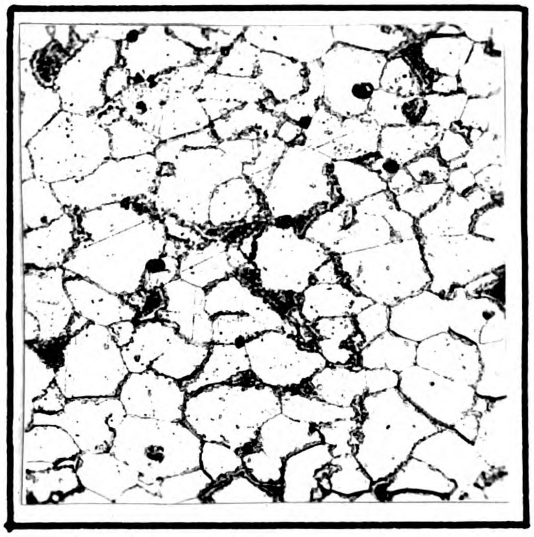
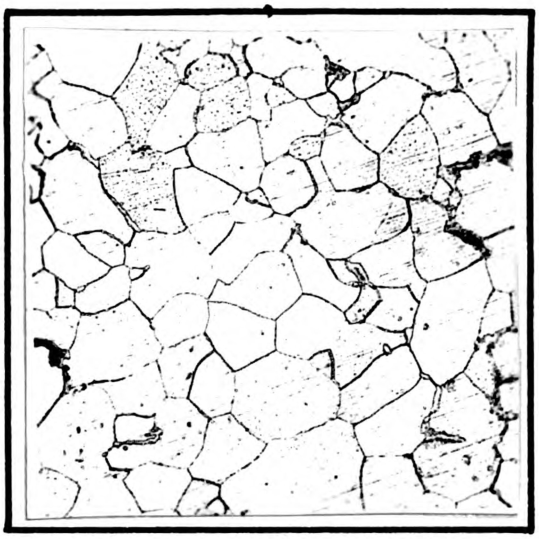
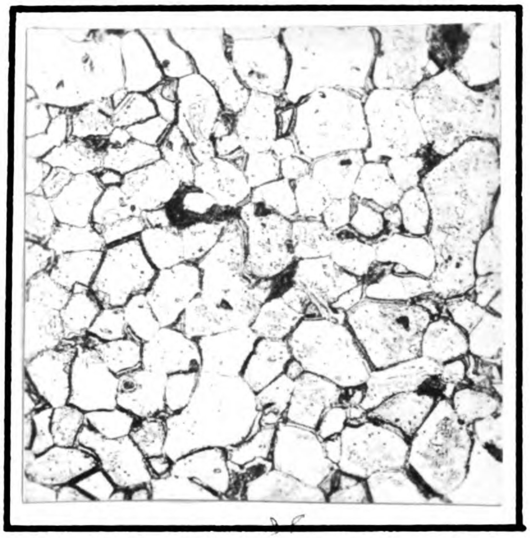
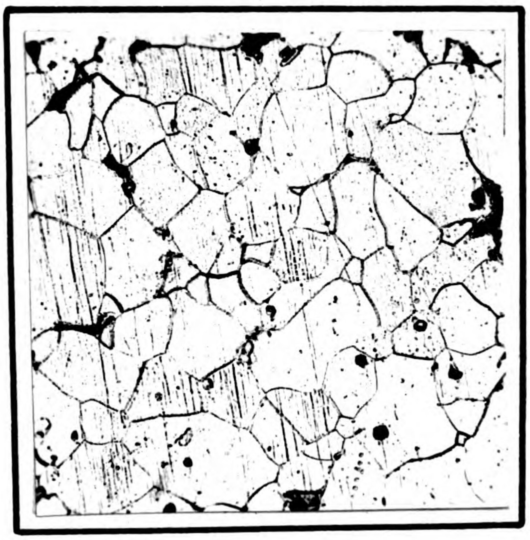
Figure No. 38.
Specimen No. B_1
(center). 250X.

Figure No. 39.
Specimen No. B_2
(edge). 250X.

Figure No. 40.
Specimen No. B_2
(center). 250X.

Figure No. 41.
Specimen No. B_3.
(edge). 250X.

Figure No. 42.
Specimen No. B_3
(center). 250X.


where the bending of the metal took place, thus disagreeing with the theory in this instance that hardness increases with reduction in area; (2) The hardness otherwise throughout the section was about the same, from 65 to 75 Rockwell "B"; and (3) For hardness readings in the region near the edge of the metal where decarburization had taken place, the hardness reading were considerable less, from 50 to 60 Rockwell "B", possibly also due to the fact that the ball point of the tester penetrated too near the edge of the metal.

SECTION "B"

This section was analyzed in about the same general manner as Section "A". Photomicrographs were taken at 100X, 250X, and 1000X. Figures No. 31 to 36, inclusive, taken at 100X, show this section (see Figure No. 2) to be somewhat uniform in grain size, with no evidences of the "killed" steel exhibited in Section "A", due to the fact that this strip was cut from a different section of the ingot and possibly from a different ingot entirely.

Figures Nos. 37 to 42, inclusive, show the grains to be in general of polyhedral structure, with very little distortion in evidence. Even at this magnification, there seems to be some white strips (possibly cementite) in the grain boundaries, this phenomena being present in each of the figures named. There seemed to be more cementite in the grain boundaries than in Specimen "A", Figures No. 43 to 48, inclusive,(taken at 1000X) indicating this fact. Again the cementite appeared in the grain boundaries and also in the form of "divorced" cementite. The location of these white strips is clearly defined upon the tissue identifying the photomicrographs.

In the photomicrographs at 250X and 1000X, there appeared several indications that larger grains had been fragmented into two or more smaller grains, but the number fragmented appeared to be less than in Section "A".

Figure No. 43.
Specimen No. B_1.
Thick white strip
in grain boundary.
1000X.

Figure No. 44.
Specimen No. B_1.
More white strips
in grain bound-
aries. 1000X.

Figure No. 45.
Specimen No. B_2.
Abundance of white
strips in grain
boundaries. 1000X.

Figure No. 46.
Specimen No. B_2.
Divorced cement-
ite around Pear-
lite. 1000X.

Figure No. 43.
Specimen No. B_1.
Thick white strip
in grain boundary.
1000X.

Figure No. 44.
Specimen No. B_1.
More white strips
in grain bound-
aries. 1000X.

Figure No. 45.
Specimen No. B_2.
Abundance of white
strips in grain
boundaries. 1000X.

Figure No. 46.
Specimen No. B_2.
Divorced cement-
ite around Pear-
lite. 1000X.

Figure No. 47. Specimen No. B_2. 1000X. Notice predominence of white strips in grain boundaries. Seems to surround Pearlite and then shoot out along grain boundaries.

Figure No. 48. Specimen No. B_2. 1000X. Strip of cementite between two large pearlite grains seems to have cut large ferrite grain in half.

Figure No. 47. Specimen No. B_2. 1000X. Notice predominence of white strips in grain boundaries. Seems to surround Pearlite and then shoot out along grain boundaries.

Figure No. 48. Specimen No. B_2. 1000X. Strip of cementite between two large pearlite grains seems to have cut large ferrite grain in half.

Specimen B_1 (see Table No. 3) measured .1153 inches in diameter, as compared with .1406 inches for Specimen B_3, a reduction in cross-sectional area of 18%. For this reduction of area, there was an accompanying reduction in grain size of only 8.1% as compared with 36% in Section "A". Furthermore, specimen B_2 showed an increase in grain size over B_3, rather than a reduction, there being a 1.7% increase. However, by counting the number of grains in Figures 42 and 44, there was found to be 114 grains in the photomicrograph of B_2, and 96 in B_3. This would indicate a reduction of 16% in grain size in B_2 relative to the size exhibited in B_3.

Again referring to Table No. 5 and Figure No. 2a, the hardness values for this section will be found to agree quite closely with that of Section "A", with increased hardness indicated at the places in the steel where a bending occurred.

Summarizing, Section "B", after undergoing the second cold-working operation, exhibited practically the same generally characteristics as Section "A", though the two sections are two different pieces of metal. The grain size of the two sections were in the sam range and but little more reduction in area had taken place. The cementite areas seemed to be more numerous than in Section "A". Another section, that of the final pressing operation, will next be investigated, and should this section agree appreciably with the two just analyzed, is is then thought that for this type of steel, the properties exhibited may be termed characteristic for cold-worked metal of this type.

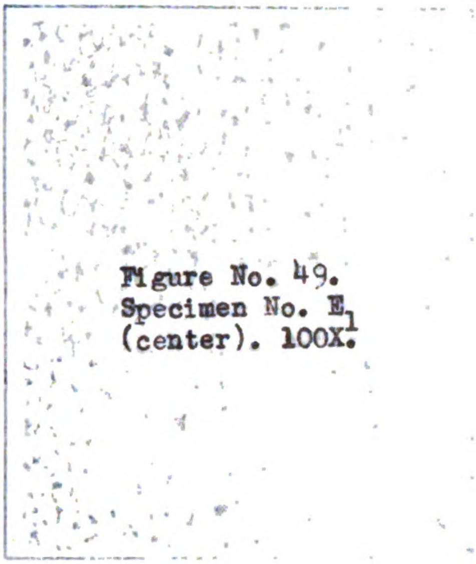


Figure No. 49.
Specimen No. E_1
(center). 100X.

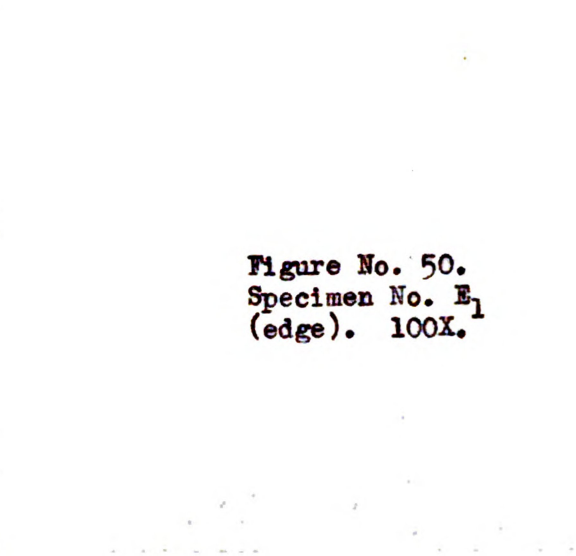


Figure No. 50.
Specimen No. E_1
(edge). 100X.

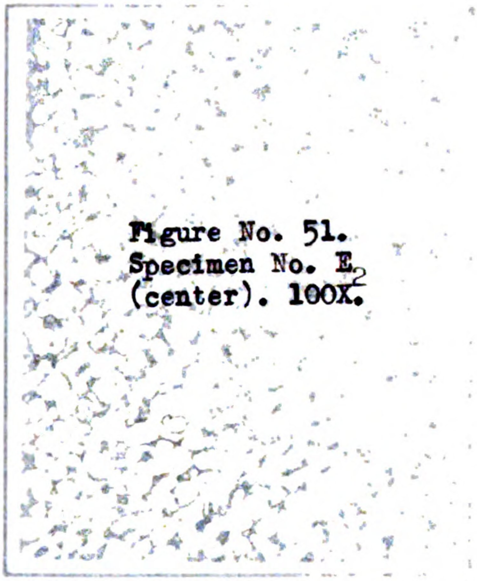


Figure No. 51.
Specimen No. E_2
(center). 100X.

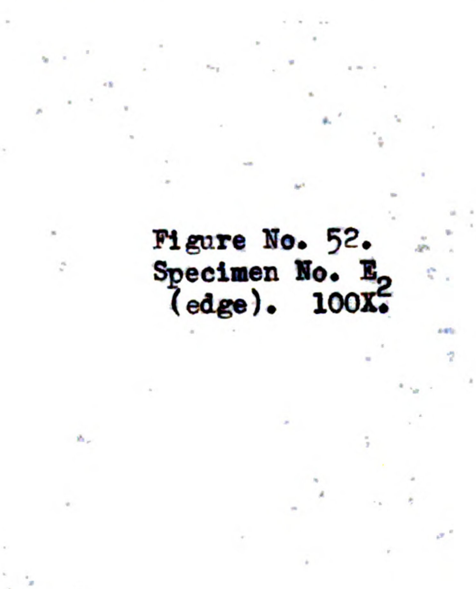


Figure No. 52.
Specimen No. E_2
(edge). 100X.

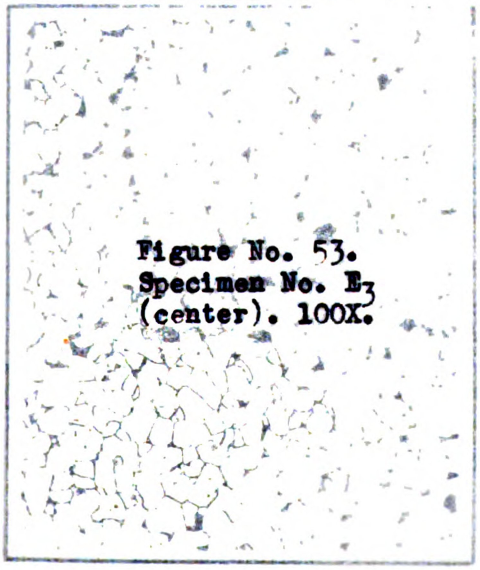


Figure No. 53.
Specimen No. E_3
(center). 100X.

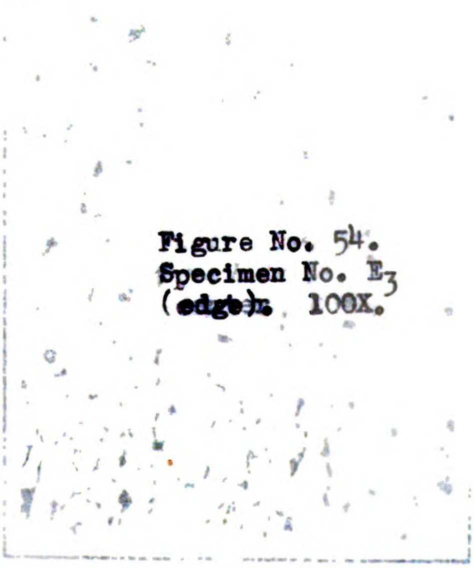


Figure No. 54.
Specimen No. E_3
(edge). 100X.

Figure No. 49.
Specimen No. E_1
(center). 100X.

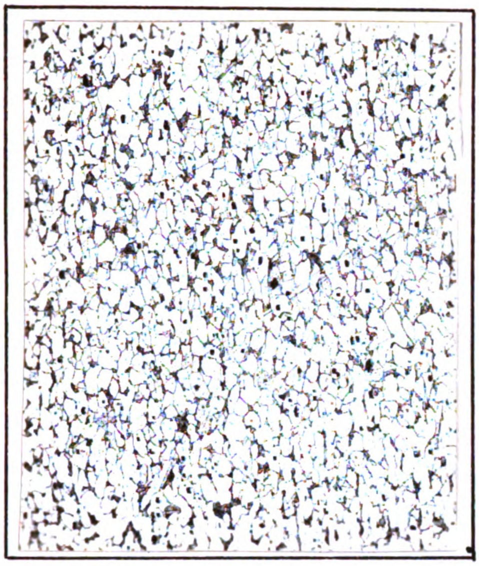
Figure No. 50.
Specimen No. E_1
(edge). 100X.

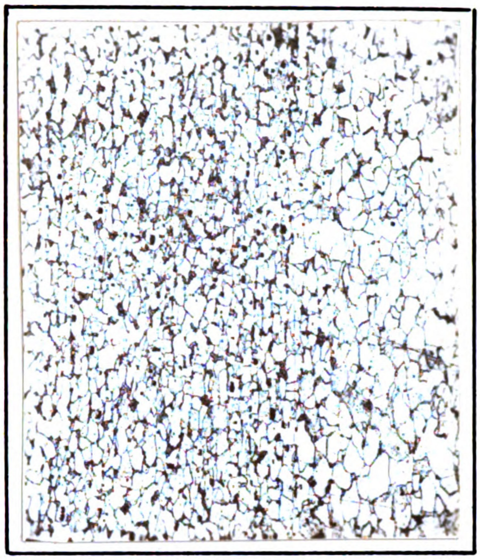
Figure No. 51.
Specimen No. E_2
(center). 100X.

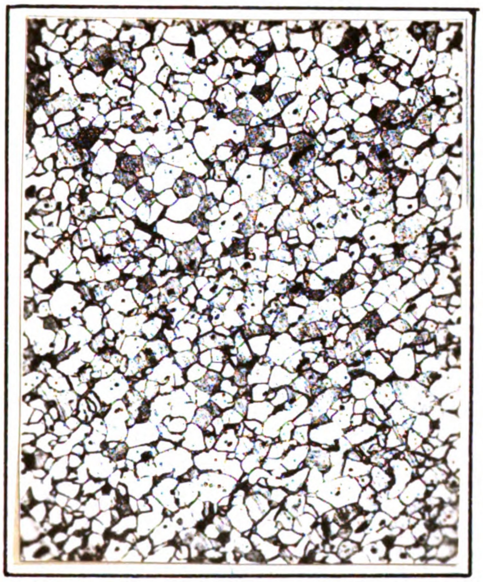
Figure No. 52.
Specimen No. E_2
(edge). 100X.

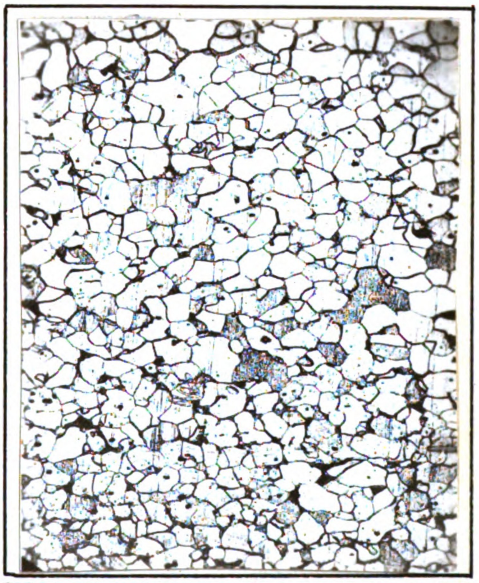
Figure No. 53.
Specimen No. E_3
(center). 100X.

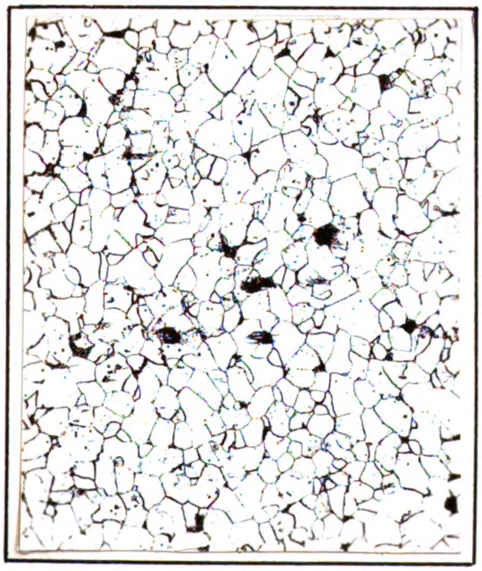
Figure No. 54.
Specimen No. E_3
(edge). 100X.











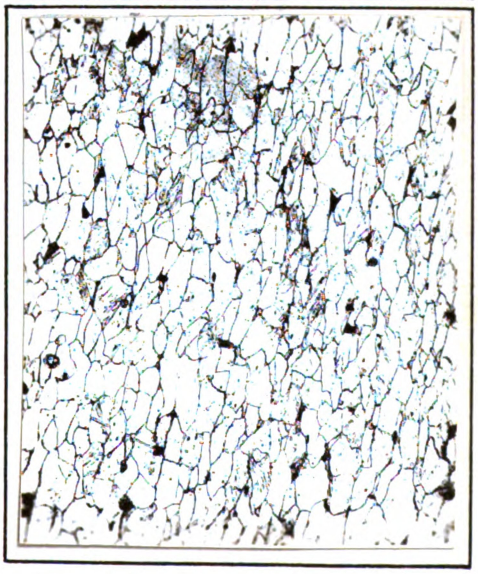


Figure No. 55. Specimen No. E_3. Taken at 100X. Showing grain structure across distorted section.

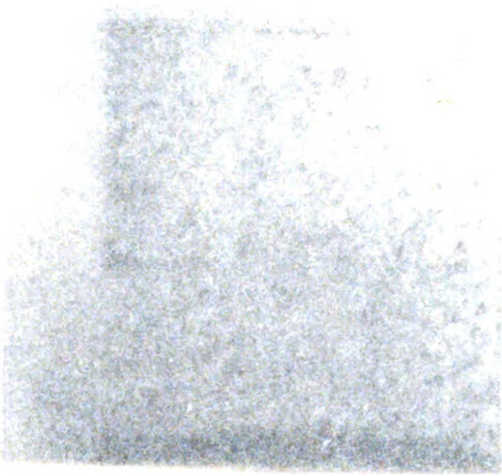
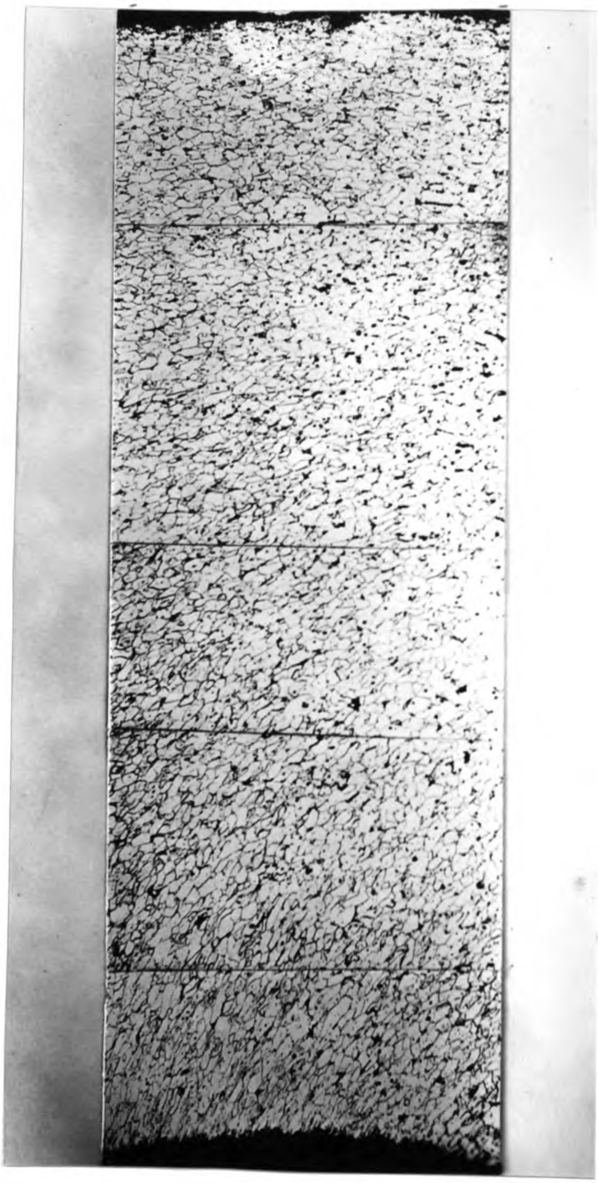


Figure No. 55. Specimen No. E_3. Taken at 100X. Showing grain structure across distorted section.



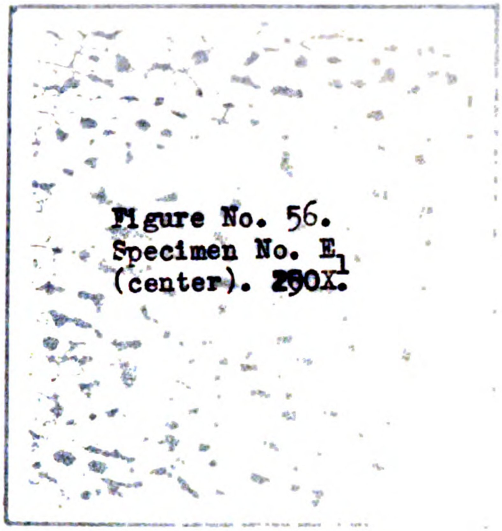


Figure No. 56.
Specimen No. E_1
(center). 250X.

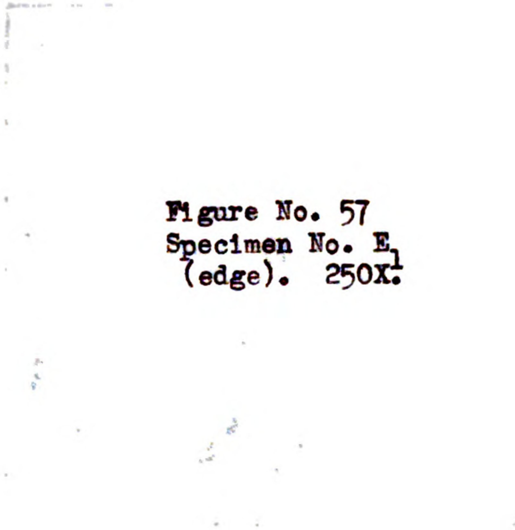


Figure No. 57
Specimen No. E_1
(edge). 250X.

Figure No. 58
Specimen No. E_2
(center). 250X.

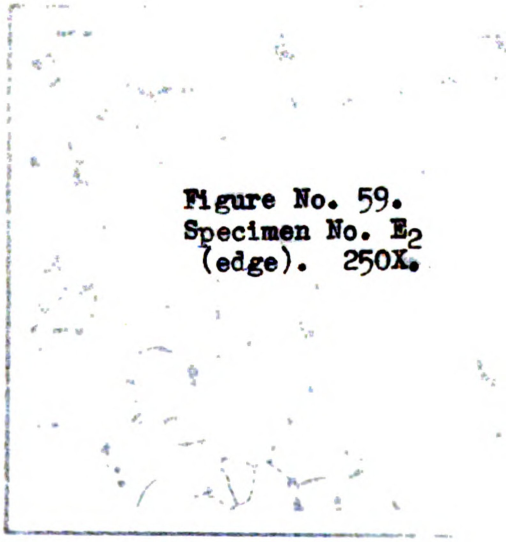


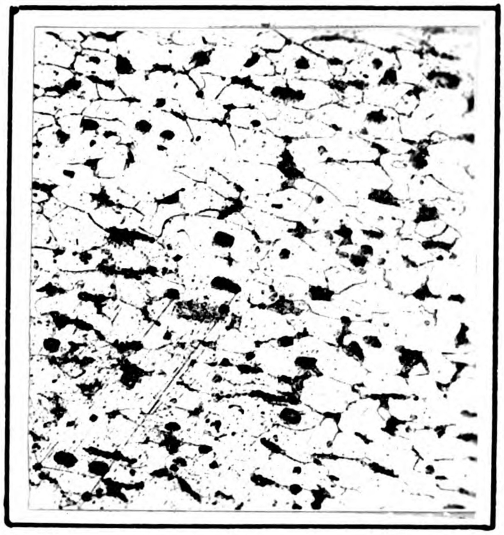
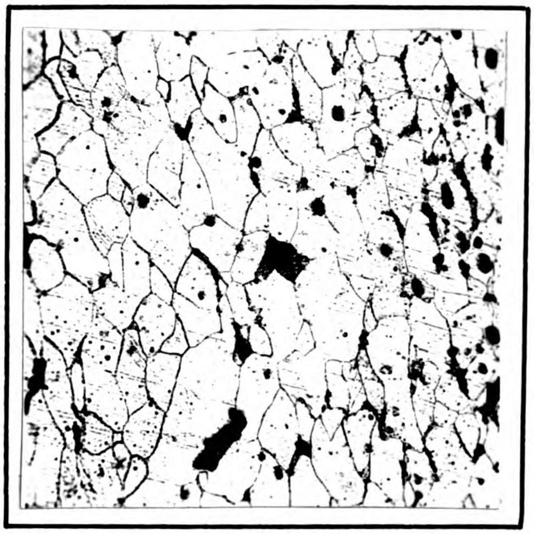
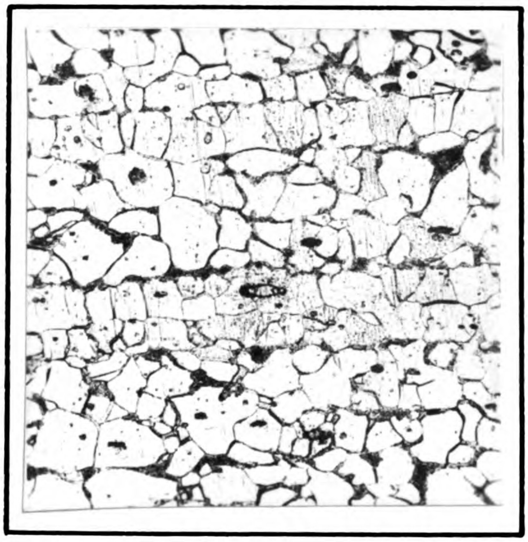
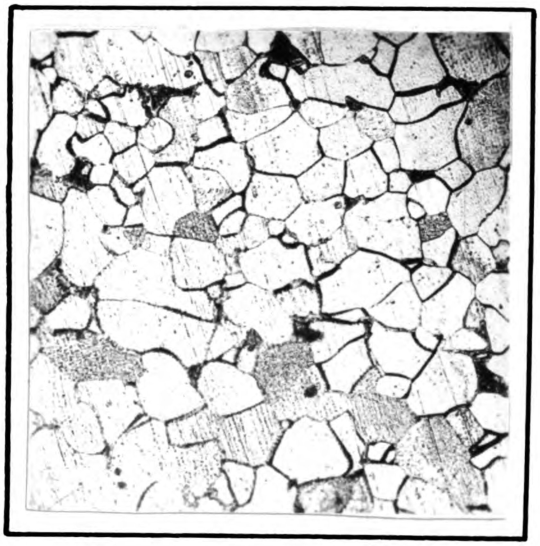
Figure No. 59.
Specimen No. E_2
(edge). 250X.

Figure No. 56.
Specimen No. E_1
(center). 250X.

Figure No. 57
Specimen No. E_1
(edge). 250X.

Figure No. 58
Specimen No. E_2
(center). 250X.

Figure No. 59.
Specimen No. E_2
(edge). 250X.

SECTION "E"

Figure No. 49 showed at 100X that E_1 was a very fine grained metal with "ghost" lines present. Figure No. 50 of the same specimen showed that the grains near the edge of the specimen were larger, again indicating the presence of a "killed" steel. Figures No. 51, 52, and 53 show somewhat uniform structures but larger grained than Specimen E_1. The first real evidence of distortion to any marked degree is exhibited in the photomicrograph of the edge of Specimen E_3 (Figure No. 54), this picture being taken at the point of the bend in this piece. It is quite evident that the cold working at this point has elongated the grains, due of course to the fact that the elastic point of the metal has been exceeded in the bending operation.

Figure No. 55 shows a composite picture taken across Specimen E_3 at the point of bending and distortion is in evidence at both edges of the metal. These pictures were taken at 100X and in a series across the specimen.

In the photomicrographs taken at 250X, Figures No. 56 to 63, inclusive, the structure is noted as polyhedral, generally undistorted, and gave evidence of grain fragmentation. In Figures No. 54 and No. 55, (of Specimen E_1) distortion was present in a more advanced degree than any other specimen analyzed except that shown in the bent section of Specimen E_3. Figure No. 62, taken across the bent section of E_3 shows some distortion and a noticeable amount of grain fragmentation, while Figure No. 63 clearly shows the elongation of the grains in this same specimen.

Cementite again appeared in the grain boundaries as indicated in Figures No. 64 to 74, inclusive. It occurred in the same manner as in the previous sections, that is, in grain boundaries and surrounding Pearlitic grains. Grain fragmentation was especially noticeable in Figures No. 71 to 74, inclusive. These photomicrographs were taken at 1000X.

From Table No. 4, it will be seen that Specimen E_1 had an average diameter of .0922 inches as compared with .1359 inches for Specimen E_3, a reduction in

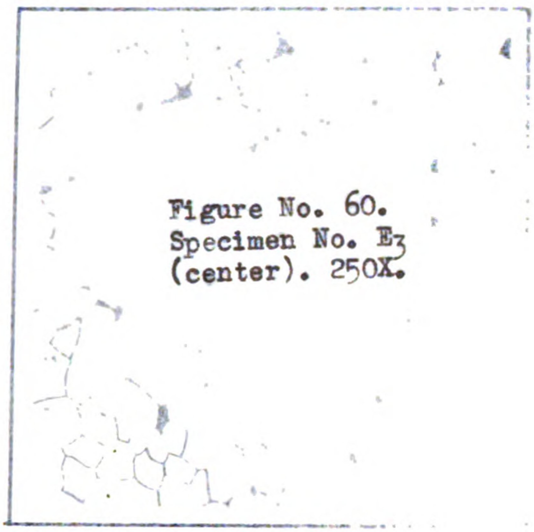


Figure No. 60.
Specimen No. E_3
(center). 250X.

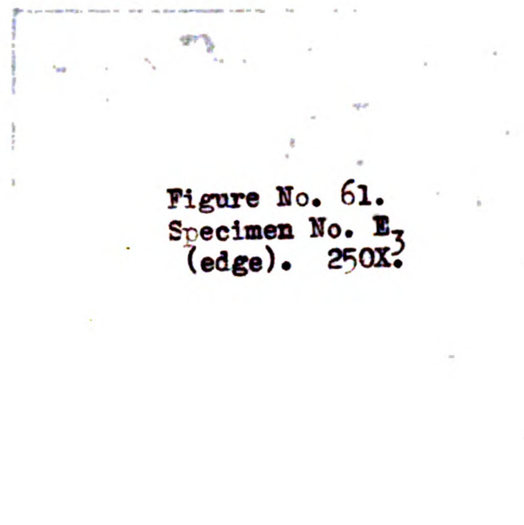


Figure No. 61.
Specimen No. E_3
(edge). 250X.

Figure No. 62.
Specimen No. E_3
(center). 250X.

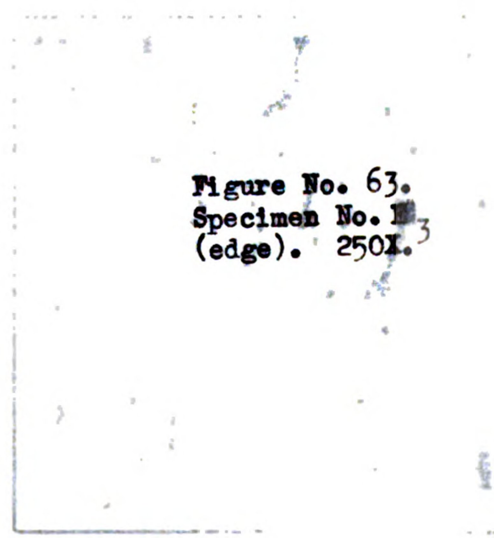


Figure No. 63.
Specimen No. E_3
(edge). 250X.

Figure No. 60.
Specimen No. E_3
(center). 250X.

Figure No. 61.
Specimen No. E_3
(edge). 250X.

Figure No. 62.
Specimen No. E_3
(center). 250X.

Figure No. 63.
Specimen No. E_3
(edge). 250X.

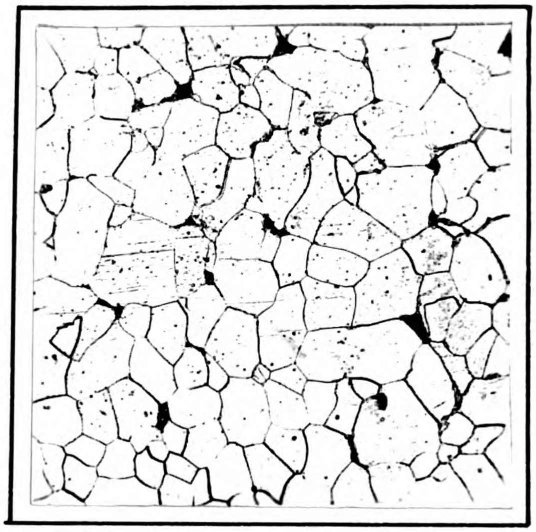
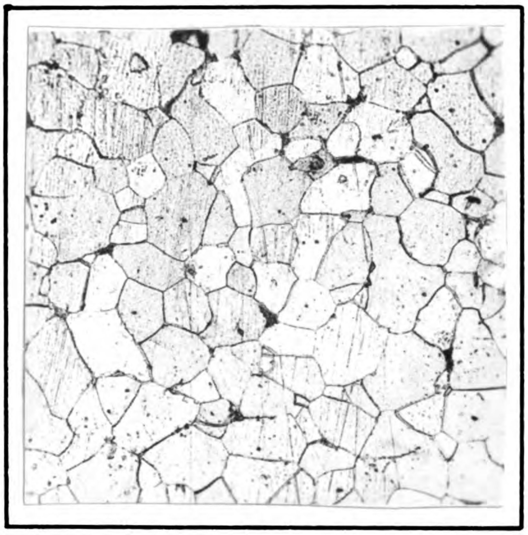
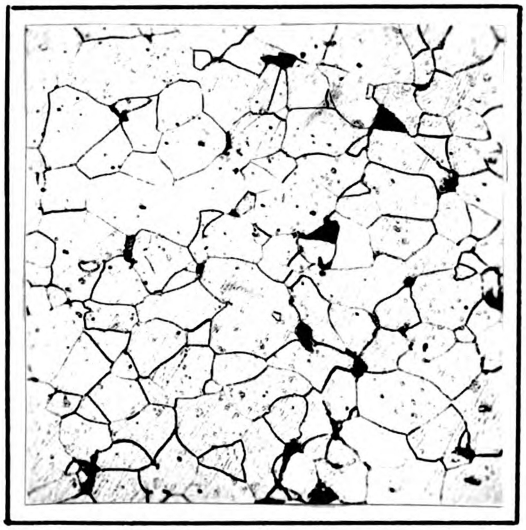
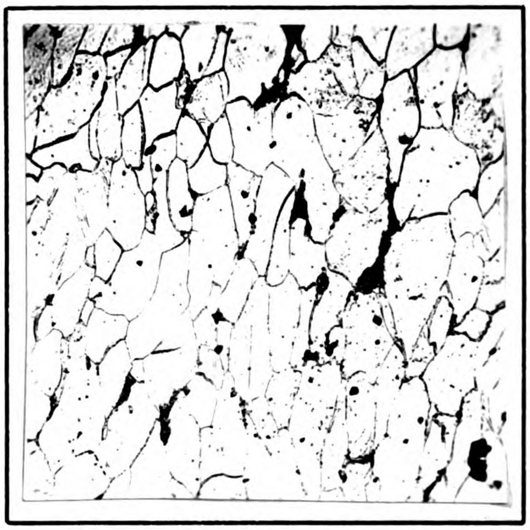
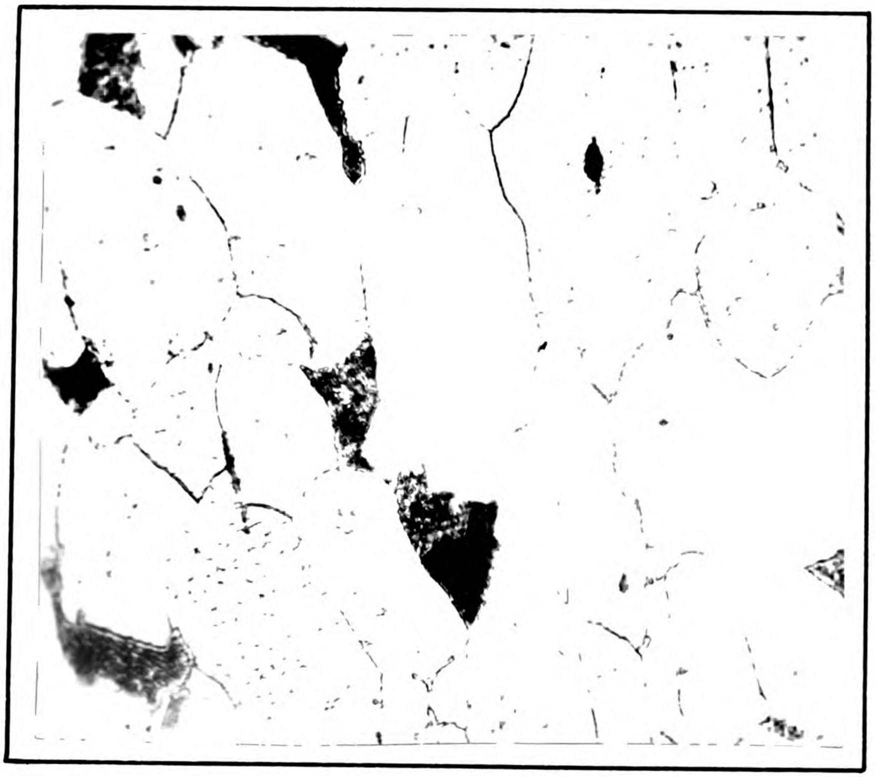





Figure No. 64. Specimen No. E_1. 1000X. Cementite predominantly present. Small carrot shaped grain apparently fractured.

Figure No. 65. Specimen No. E_2 1000X. Divorced cementite and white strips in grain boundaries.

Figure No. 64. Specimen No. E_1.
1000X. Cementite predominantly
present. Small carrot shaped grain
apparently fractured.

Figure No. 65. Specimen No. E_2
1000X. Divorced cementite and
white strips in grain boundaries.



area of 32.2%, practically double that of the first two pressing operations. For this reduction in area, an accompanying reduction in grain size of 37.2% was determined, this being about the same reduction in grain size exhibited by Section A. Distortion was beginning to be noticeable in the thinned out Specimen E_1, where this reduction took place. In counting grains across the distorted or bent section of E_3, it was noticed that the number was greater than for any other specimen in this section, indicating that the grains had been elongated in the direction of the length of the piece.

From Table No. 5, the hardness values for this section (see Figure No. 2a) were found somewhat uniform through out, except at the point of bends where the hardness was generally greater. The hardness values agreed to within five or ten points Rockwell with Section A, thus showing that the average hardness of Section E had not increased appreciably with the reduction in area and cold-working. However, it must be remembered again that Section A is an entirely different piece of metal than Section E, and therefore cannot be taken as absolute proof that the hardness has not increased, even though such seems to be the indication.

DATA

Table No. 1 shows the count of grains, average diameter, number of grains per 0.1 inch, reduction in area, reduction in grain size, and number of grains if there had not been a reduction in grain size with reduction in area; these being determined from Section A.

Table No. 3 and No. 4 show the same properties for Sections B and E, respectively.

Table No. 2 indicates the results obtained from counting the grains upon the composite pictures of Specimens A_1 and A_3, taken at 500X, and then noting the reduction in grain size as compared with Table No. 1.

Table No. 5 exhibits the hardness readings as taken at the points

Specimen No. E_2. Figure No. 66. 1000X. Notice long white strips in grain boundaries in central portion of picture.

Specimen No. E_2. Figure No. 67. 1000X. Notice long white strip which is apparently severing grain.

Specimen No. E2. Figure No. 66.
1000X. Notice long white strips in
grain boundaries in central portion
of picture.

Specimen No. E_2. Figure No. 67.
1000X. Notice long white strip
which is apparently severing
grain.

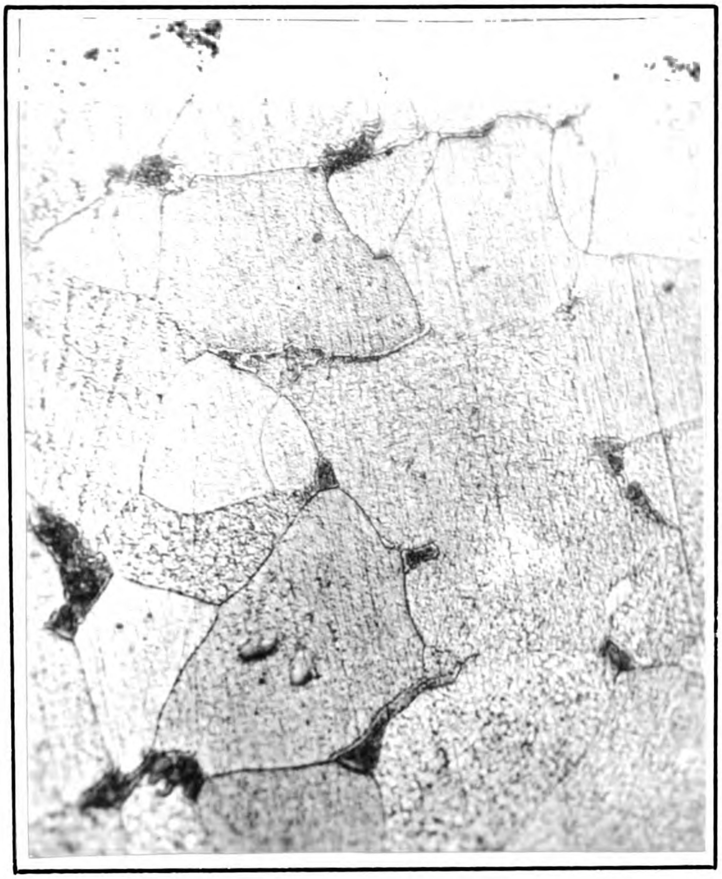
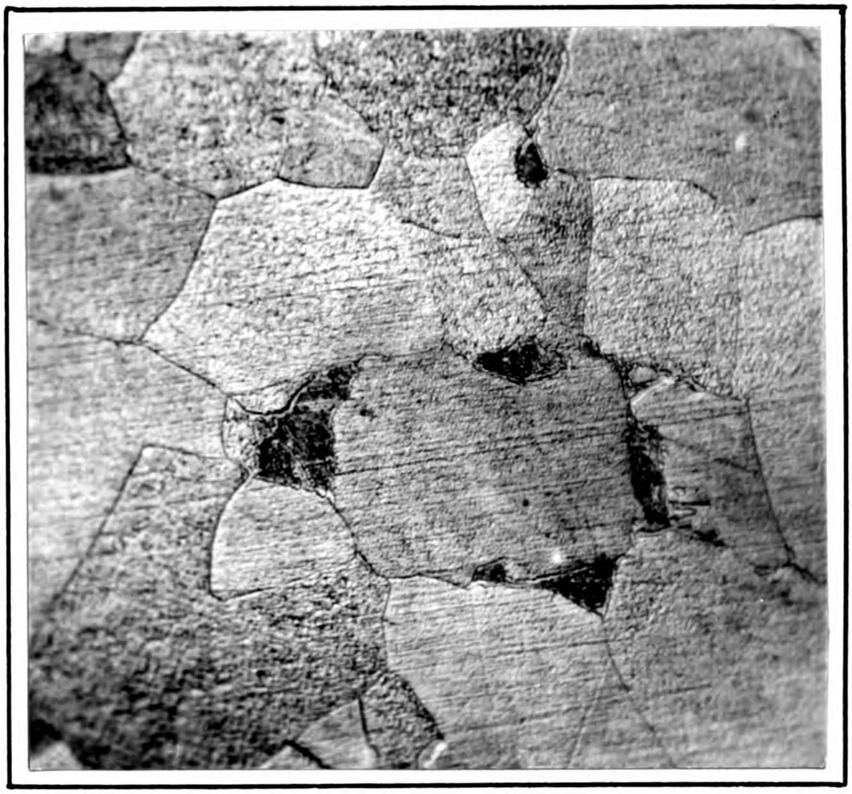


Figure No. 68. Specimen No. E_2. 1000X. Divorced cementite present. Grain boundaries at various points contain irregular strips of white.

Figure No. 69. Specimen No. E_2. 1000X. Cementite predominant in grain boundaries.

Figure No. 68. Specimen No. E_2.
1000X. Divorced cementite present.
Grain boundaries at various points
contain irregular strips of white.

Figure No. 69. Specimen No. E_2.
1000X. Cementite predominant in
grain boundaries.



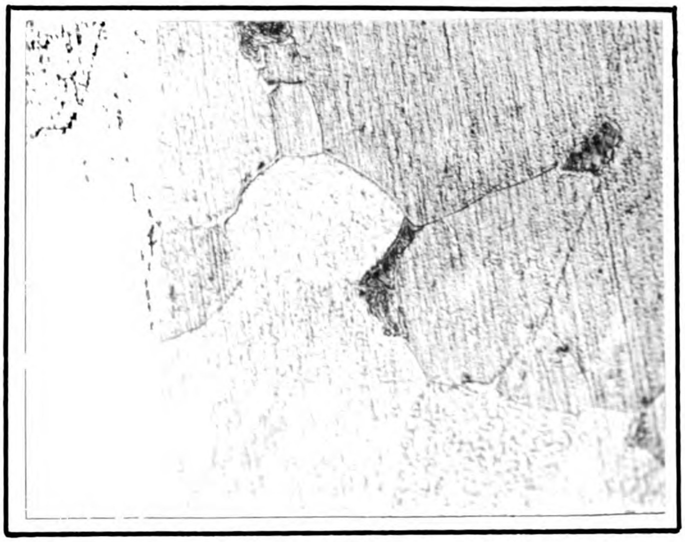
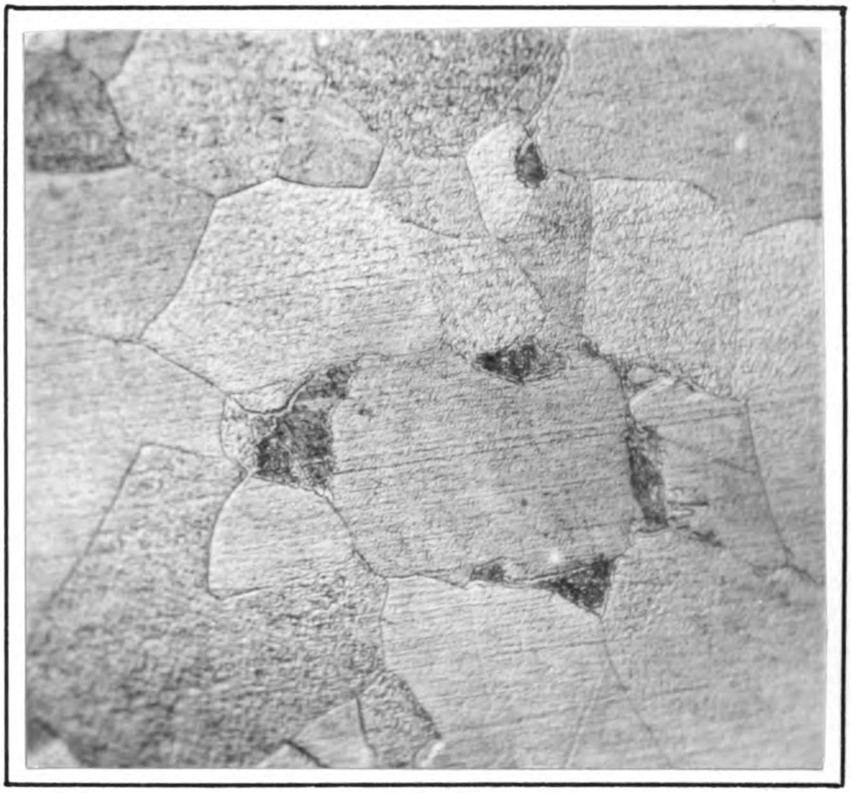


Figure No. 68. Specimen No. E_2.
1000X. Divorced cementite present.
Grain boundaries at various points
contain irregular strips of white.

Figure No. 69. Specimen No. E_2.
1000X. Cementite predominant in
grain boundaries.



indicated in Figure No. 2a.

Table No. 6 is an index to the photomicrographs included in the thesis.

Figure No. 70. Specimen No. E_3. 1000X. Rectangular Pearlite grain surrounded by divorced cementite.

Figure No. 70. Specimen No. E_3.
1000X. Rectangular Pearlite grain
surrounded by divorced cementite.

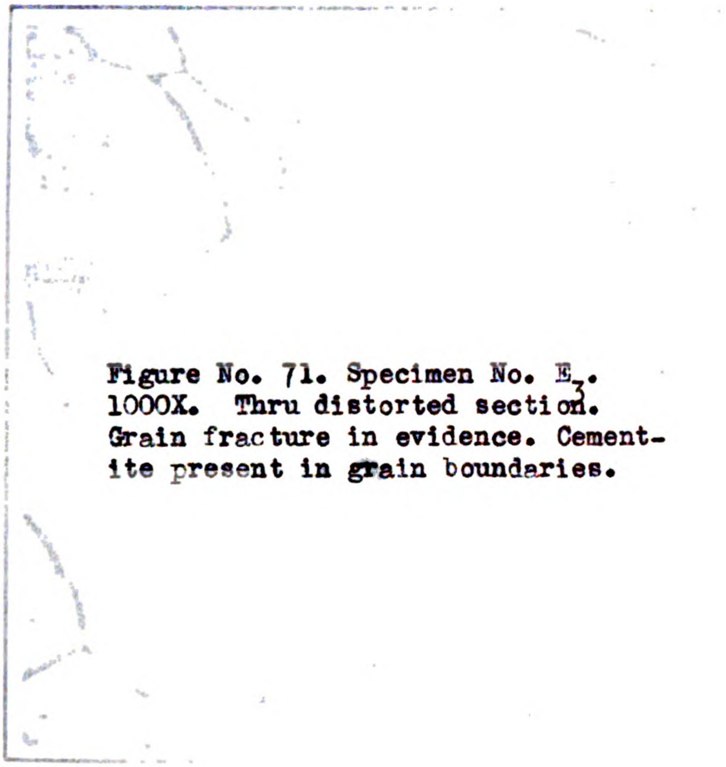


Figure No. 71. Specimen No. E_3. 1000X. Thru distorted section. Grain fracture in evidence. Cementite present in grain boundaries.

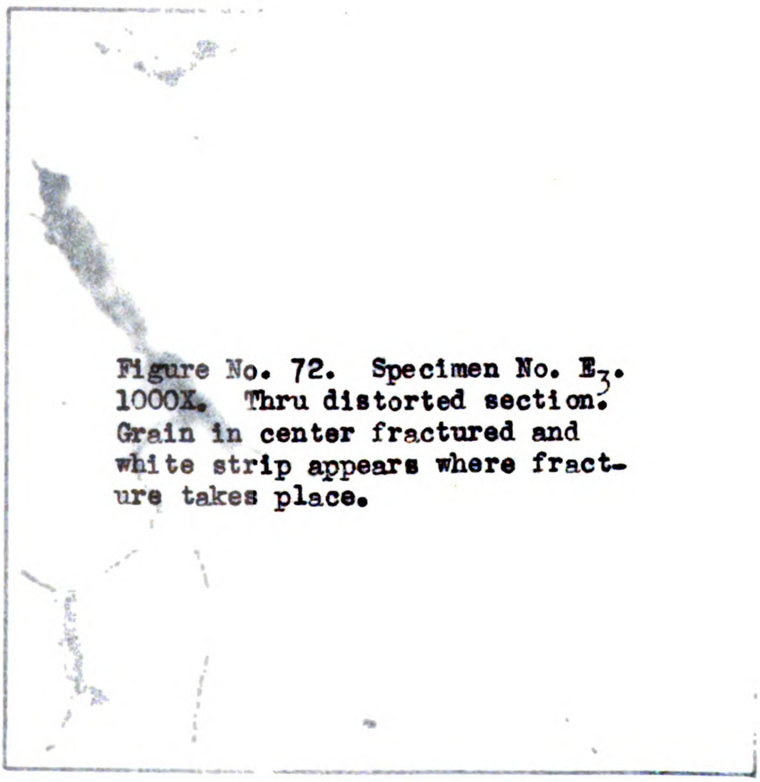


Figure No. 72. Specimen No. E_3. 1000X. Thru distorted section. Grain in center fractured and white strip appears where fracture takes place.

Figure No. 71. Specimen No. E_3.
1000X. Thru distorted section.
Grain fracture in evidence. Cement-
ite present in grain boundaries.

Figure No. 72. Specimen No. E_3.
1000X. Thru distorted section.
Grain in center fractured and
white strip appears where fract-
ure takes place.

Figure No. 73. Specimen No. E_3. 1000X. Thru distorted section. Long carrot-shaped grain in center of picture apparently cut in two by a grain which is in turn fractured.

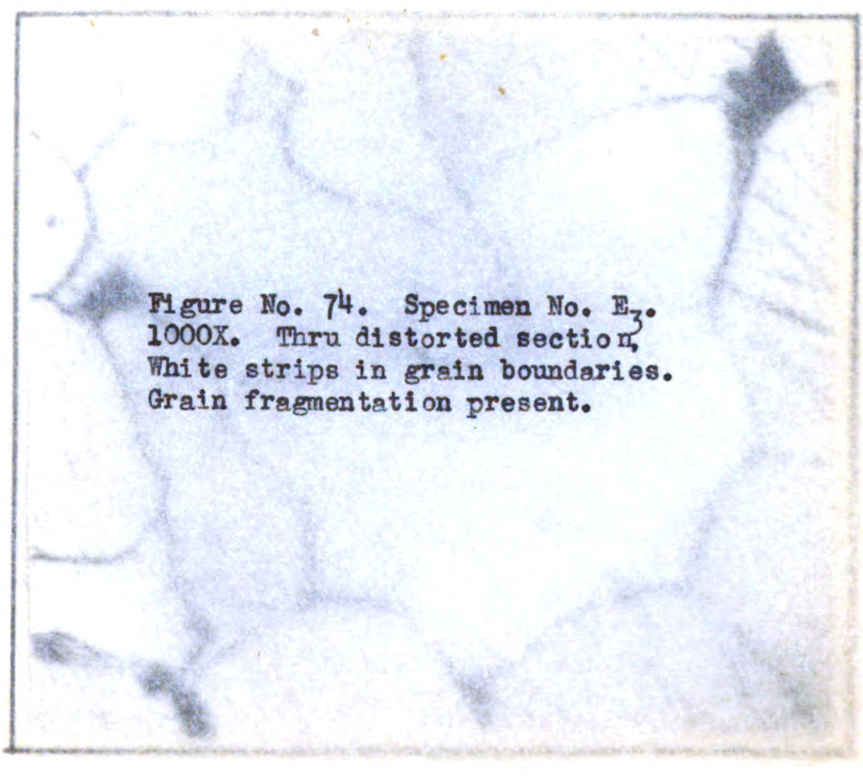
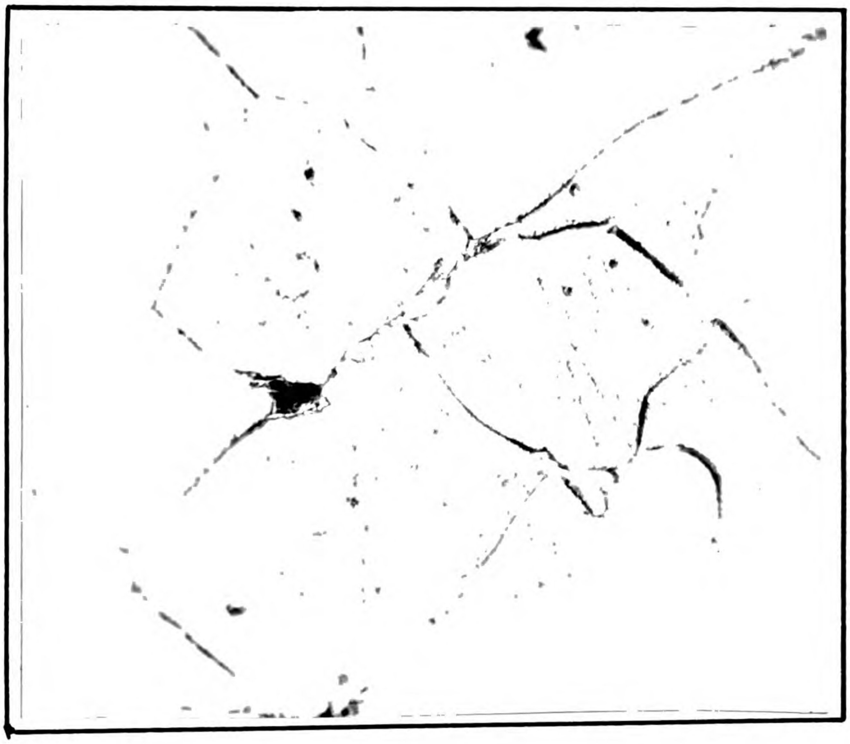


Figure No. 74. Specimen No. E_3. 1000X. Thru distorted section. White strips in grain boundaries. Grain fragmentation present.

Figure No. 73. Specimen No. E_3.
1000X. Thru distorted section.
Long carrot-shaped grain in center
of picture apparently cut in two
by a grain which is in turn fract-
ured.

Figure No. 74. Specimen No. E_3.
1000X. Thru distorted section.
White strips in grain boundaries.
Grain fragmentation present.



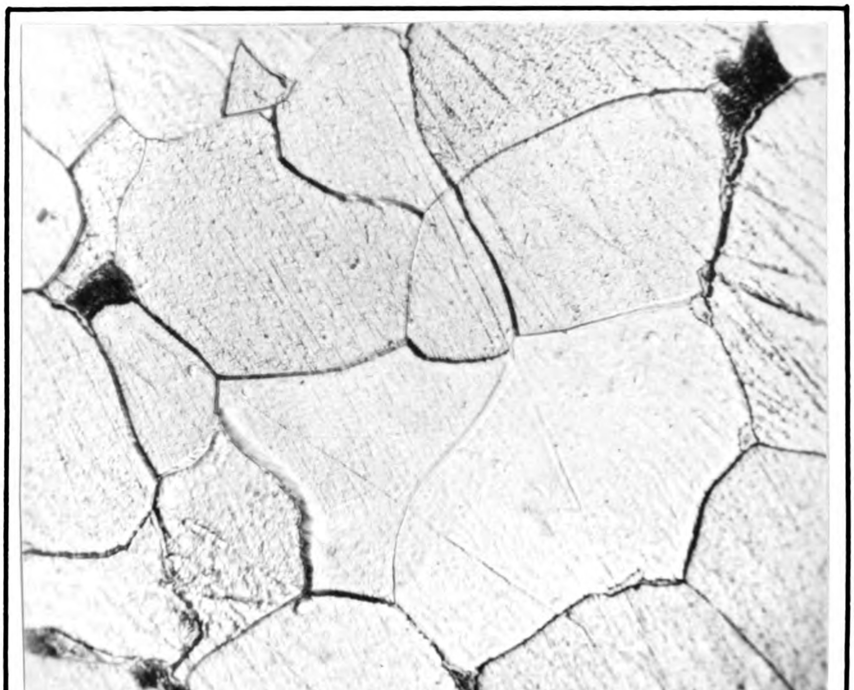


TABLE NO. 1
SHOWING COLD-WORK EFFECTS UPON
SECTION NO. "A".

Section No.	Specimen No.	Average Diameter (inches)	Number of Grains Counted Across Diameter - 4 places. A	B	C	D	Average	Number Grains per 0.1 inch	Reduction in Area (%)	Reduction in Grain Size (%)	Number Grains if no Decrease in Grain Size
A	A_1	.1323	116	123	129	126	123	93	unity	unity	unity
A	A_2	.1126	164	175	155	174	167	148	15%	37.3%	104.5
A	A_3	.1131	154	167	173	161	164	145	14.7%	36.0%	105.0
A	A_4	.1245	174	176	140	154	161	129	6.0%	28.0%	115.8
A	A_5	.1301	140	132	136	148	139	106	1.7%	13.7%	120.2
A	A_6	.1253	172	166	170	157	166	132	5.4%	30.2%	116.4

TABLE NO. 2
SHOWING COMPARATIVE DATA OBTAINED
FROM 500X COMPOSITE PHOTOMICROGRAPH

Section No.	Specimen No.	Edge of Specimen	Number of Grains Counted As Measured on 500X Picture-12 inches A	B	C	D	Average	Number Grains per inch of Photomicrograph	Reduction in Grain Size (%)
A	A_1	Left	25	27	24	25	25.25	2.10	Unity
A	A_1	Right	21	19	25	22	21.75	1.81	Unity
A	A_3	Left	34	32	31	32	32.25	2.73	23.0%
A	A_3	Right	33	32	30	31	31.50	2.63	31.2%

TABLE NO. 3
SHOWING COLD-WORK EFFECTS UPON
SECTION NO. "B".

Section No.	Specimen No.	Average Diameter (inches)	Number of Grains Counted Across Diameter - at 4 Places A	B	C	D	Average	Number Grains per 0.1 inch	Reduction in Area (%)	Reduction in Grain Size (%)	Number Grains if no Decrease in Grain Size
B	B_1	.1153	140	143	120	130	134	116	18%	8.1%	123.1
B	B_2	.1325	136	122	141	159	140	106	-5.2%	-1.7%	142.3
B	B_3	.1406	149	155	148	148	150	107	unity	unity	unity

TABLE NO. 4
SHOWING COLD-WORK EFFECTS UPON
SECTION NO. "E".

Section No.	Specimen No.	Average Diameter (inches)	Number of Grains Counted Across Diameter - at 4 Places A	B	C	D	Average	Number Grains per 0.1 inch	Reduction in Area (%)	Reduction in Grain Size (%)	Number Grains if no Decrease in Grain Size
E	E_1	.0922	156	180	165	169	168	182	32.2%	37.2%	108.5
E	E_2	.1248	165	152	170	176	166	133	8.2%	11.6%	146.9
E	E_3	.1359	162	163	158	155	160	118	unity	unity	unity

TABLE NO. 5
ROCKWELL HARDNESS DETERMINATIONS**

Reading No.	Section "A"	Section "B"	Section "E"
1	76	77	89
2	79	73	90
3	62	68	74
4	77	66	77
5	80	77	87
6	79	71	79
7	84	81	82
8	84	83	85
9	84	83	80
10	84	81	79
11	76	80	86
12	70	76	87
13	75	73	74
14	70	70	60
15	63	74	60
16	71	70	83
17	75	70	52
18	73	71	75
19	80	74	77
20	78	79	79
21	79	84	87
22	75	82	85
23	80	80	85
24	83	82	84
25	82	77	84
26	62	77	82
27	57	79	80
28	67	79	80
29	74		80
30	77		83
31	73		

** - See figure No. 2a for points upon each section where hardness readings taken. All readings in Rockwell "B" scale.

TABLE NO. 6

INDEX TO PHOTOMICROGRAPHS

Figure No.	Specimen No.	Eye Piece	Objective	Bellows Length (cm)	Magnification (X)	Remarks
4	A_1	7.5	16 mm	27	100	Grains uniform - no evidence of killed steel.
5	A_2 center	7.5	16 mm	27	100	"Ghost lines" throughout picture.
6	A_2 edge	7.5	16 mm	27	100	Larger grains near bottom are at edge of specimen. "Killed" steel shown here.
7	A_3 edge	7.5	16 mm	27	100	Killed steel and ghost lines in evidence. Decarburized area at bottom of picture.
8	A_3 center	7.5	16 mm	27	100	"Ghost lines" throughout.
9	A_4 edge	7.5	16 mm	27	100	"Ghost lines" and larger grains at edge of specimen.
10	A_4 center	7.5	16 mm	27	100	"Ghost lines" throughout.
11	A_5 edge.	7.5	16 mm	27	100	Larger grains at edge of specimen.
12	A_5 center	7.5	16 mm	27	100	Ghost lines present.
13	A_6	7.5	16 mm	27	100	Grains uniform - no evidence of killed steel.
14	A_1 center	7.5	8 mm	34.5	250	Grains polyhedral. Some indications of larger grains beginning to break up.
15	A_1 edge	7.5	8 mm	34.5	250	Same as Figure No. 14. In these figures, notice white strips in grain boundaries.
16	A_4 center	7.5	8 mm	34.5	250	Smaller grain. Fragmentation present. "Ghost lines" present.
17	A_4 edge	7.5	8 mm	34.5	250	Polyhedral grain structure. White strips in grain boundaries and in pearlite. White strips in places appear to sever portion from large grain.

TABLE NO. 6
(Continued)

Figure No.	Specimen No.	Eye Piece	Objective	Bellows Length (cm)	Magnification (X)	Remarks
18	A_2 center	7.5	8 mm	34.5	250	"Ghost lines" present. Notice grain fragmentation.
19	A_2 edge	7.5	8 mm	34.5	250	Grain fragmentation present. Polyhedral structure.
20	A_2 edge	7.5	1.8mm	34.5	1000	Notice how small parts apparently severed from larger grain. Cementite in junction of grain boundary and also partially surrounding pearlite grain.
21	A_2 center	7.5	1.8mm	34.5	1000	Grain fragmentation present. Some cementite present in grain boundary. Notice one large grain in center which has apparently been elongated and broken into two parts.
22	A_4 center	12.5	5.5mm	31.0	500	Cementite in grain boundaries. Notice grain fragmentation. Some distortion present.
23	A_1	7.5	1.8mm	34.5	1000	Divorced cementite almost completely encircleing long pearlite(black) grain.
24	A_1	12.5	6mm U.V.	70.0	1000	Taken in Ultra Violet Light-exposure time : 405 minutes. Divorced cementite around pearlite grain and narrow strip of cementite extending in grain boundary from pearlite.
25	A_1	7.5	1.7 U.V.	32.0	1000	Taken in Ultra Violet Light - exposure time : 50 minutes. Notice white strip in upper portion of picture. Other less noticeable cementite present.
26	A_1	12.5	5.5mm	58.0	1000	White strips in grain boundaries. Divorced cementite in center of picture. What is the nature of strip between grains?
27	A_1	12.5	6mm U.V.	70.0	1000	Photographed in Ultra Violet - Exposure time: 515 minutes. Compare with Figure 26. More resolution.

TABLE NO. 6
(Continued)

Figure No.	Specimen No.	Eye Piece	Objective	Bellows Length (cm)	Magnification (X)	Remarks
31	B_1 center	7.5	16 mm	27.0	100	Typical low carbon steel with uniform grain structure.
32	B_1 edge	7.5	16 mm	27.0	100	Uniform structure.
33	B_2 center	7.5	16 mm	27.0	100	Notice small white strips around and near pearlite (black) grains.
34	B_2 edge	7.5	16 mm	27.0	100	Same as Figure No. 33.
35	B_3 center	7.5	16 mm	27.0	100	Uniform structure. White strips in few instances in Pearlite.
36	B_3 edge	7.5	16 mm	27.0	100	Uniform structure. White strips in grain boundaries in several instances.
37	B_1 edge	7.5	8 mm	34.5	250	Grains polyhedral. Notice long white strip in center of picture located in grain boundaries.
38	B_1 center	7.5	8 mm	34.5	250	Many white strips in grain boundaries. No distortion.
39	B_2 edge	7.5	8 mm	34.5	250	No distortion present. More white strips visible in grain boundaries. Some grain fragmentation.
40	B_2 center	7.5	8 mm	34.5	250	Apparent grain fragmentation. In some instances white strips almost entirely surround ferrite grains.
41	B_3 edge	7.5	8 mm	34.5	250	Grain fragmentation present. Divorced cementite apparently in pearlite grains.
42	B_3 center	7.5	8 mm	34.5	250	Cementite in grain boundaries. Divorced cementite present. Some grains apprantly fragmented.
43	B_1	7.5	1.8mm	34.5	1000	Laminated pearlite surrounded by divorced cementite. Notice strip or channel of cementite in grain boundaries at various points. Notice small grain apparently cut in two parts.

TABLE NO. 6
(Continued)

Figure No.	Specimen No.	Eye Piece	Objective	Bellows Length (cm)	Magnification (X)	Remarks
44	B_1	7.5	1.8mm	34.5	1000	Divorced cementite in pearlite grain. Just above pearlite, notice apparent grain fragmentation. Notice white strip of cementite in grain boundary on opposite end of picture.
45	B_2	7.5	1.8mm	34.5	1000	Notice abundance of irregular white strips in grain boundaries. White strips seem to cut large grains into several smaller ones.
46	B_2	7.5	1.8mm	34.5	1000	Divorced cementite around Pearlite. Two white strips of cementite touching each other in grain boundary away from Pearlitic grains.
47	B_2	7.5	1.8mm	34.5	1000	Cementite in grain boundaries in irregular strips. Will seem to surround Pearlite and then shoot out along grain boundary away from Pearlite. White globs seen some distance from Pearlite.
48	B_2	7.5	1.8mm	34.5	1000	Cementite in same form as above. Notice white strip connecting two pearlite grains and apparently cutting large grain in half.
49	E_1 center	7.5	16 mm	27.0	100	Shows very fine structure. "Ghost" lines present.
50	E_1 edge	7.5	16 mm	27.0	100	Portion with larger grains are the edge of the specimen. Shows "killed" steel qualities.
51	E_2 center	7.5	16 mm	27.0	100	Larger and more uniform grain structure than E_1 and no "Ghost" lines present.
52	E_2 edge	7.5	16 mm	27.0	100	Uniform grain structure. No evidence of "killed" steel.
53	E_3 center	7.5	16 mm	27.0	100	Uniform structure with apparently lower carbon content than E_1 or E_2.
54	E_3 edge	7.5	16 mm	27.0	100	Taken at portion of 90° bend. Distortion and elongation in direction of bend noticeable. Some grains appear fragmented.

TABLE NO. 6
(Continued)

Figure No.	Specimen No.	Eye Piece	Object-ive	Bellows Length (cm)	Magnification (X)	Remarks
55	E_3 across	7.5	16 mm	27.0	100	A series of five pictures pieced together to give a continuous grain structure across distorted section. Distortion in evidence at both edges.
56	E_1 center	7.5	8 mm	34.5	250	Dirty steel. Grains somewhat elongated.
57	E_1 edge	7.5	8 mm	34.5	250	Elongation present. Grain fragmentation apparent.
58	E_2 center	7.5	8 mm	34.5	250	"Ghost lines" evident. Notice grain fragmentation. Polyhedral grain structure.
59	E_2 edge	7.5	8 mm	34.5	250	Notice little grains, usually occurring in pairs, which seem to have been torn apart from larger grains.
60	E_3 center	7.5	8 mm	34.5	250	Taken away from distorted section. White areas in grain boundaries. Some fragmentation of grains.
61	E_3 edge	7.5	8 mm	34.5	250	Same as above.
62	E_3 center	7.5	8 mm	34.5	250	Some distortion present. Notice apparent grain fragmentation. Taken at point of 90° bend.
63	E_3 edge	7.5	8 mm	34.5	250	Taken at point of severe distortion. White areas in grain boundaries at several places. Some grain fragmentation.
64	E_1	7.5	1.8mm	34.5	1000	Cementite in grain boundaries. Notice small, long grain which has apparently been fragmented in half (in center of picture). Some "Divorced" cementite. Little white strips, far apart from pearlite, in grain boundaries.
65	E_2	7.5	1.8mm	34.5	1000	Notice "divorced" cementite, and white strip of cementite shooting out from pearlite to form grain boundaries. Are grain boundaries more or less made up of cementite?

TABLE NO. 6
(Continued)

Figure No.	Specimen No.	Eye Piece	Object-ive	Bellows Length (cm)	Magnifi-cation (X)	Remarks
66	E_2	7.5	1.8mm	34.5	1000	Notice long white strips in grain boundaries in center of picture. Notice at same point the large grain which has apparently broken up into three smaller grains. Divorced cementite present.
67	E_2	7.5	1.8mm	34.5	1000	Notice long, irregular strip of cementite which is apparently cutting off end of grain. Divorced cementite present.
68	E_2	7.5	1.8mm	34.5	1000	More divorced cementite present. Grain boundaries at various points contain irregular strips of cementite. Grain fragmentation noticeable.
69	E_2	7.5	1.8mm	34.5	1000	White strips predominant in grain boundaries. Does this mean that the grain boundaries contain principally cementite or as much cementite as there is "free" cementite present?
70	E_3	7.5	1.8mm	34.5	1000	Notice rectangular pearlite grain surrounded by divorced cementite. Notice several broad strips of white material in grain boundaries.
71	E_3	7.5	1.8mm	34.5	1000	Taken through distorted section. Notice elongation of grains. The long, thin grain in center of picture has been cut into two parts. Notice irregular strips of cementite present in grain boundaries.
72	E_3	7.5	1.8mm	34.5	1000	Taken through distorted section. In upper center of picture, notice white strip where long grain has been severed in half.
73	E_3	7.5	1.8 mm	34.5	1000	Taken through distorted section. Long "carrot shaped" grain apparently cut in half by long distorted grain, which was in turn, fractured. Cementite present.

TABLE NO. 6
(Continued)

Figure No.	Specimen No.	Eye Piece	Object-ive	Bellows Length (cm)	Magnifi-cation (X)	Remarks
74	E_3	7.5	1.8mm	34.5	1000	Taken through distorted section. Notice white strips in grain boundaries. Divorced cementite present. Notice large grain in uppper right hand corner which has been fragmented.

CALCULATIONS INVOLVED IN DATA

(From Table No. 1)

Number of Grains per 0.1 inch:

Average Diameter of Specimen A_2 (measured) -------------------- .1126"

Average Count of Grains across Specimen ---------------------- 167

Number of Grains/0.1" : (167/.1126) : ---------------------- 148

Reduction in Area (%):

Diameter of A_1 taken as 100% ------------------------------ .1323 in.

Diameter of A_2 -- .1126

Reduction in Area : (1 - .1126/.1323)x100------------------ 15%

Reduction in Grain Size (%): (of A_2)

No. grains across specimen if no decrease in size
(.85 x 123) ------------------------- 105

No. grains actually counted (average) across specimen --------- 167

Reduction in Grain Size : (100 - 105/167) ----------------- 37.3%

Number of Grains Across Specimen if No Decrease in Grain Size:

Number of grains across unity specimen A_1 (100%) ------------- 123

Relation of Diameter of A_2 to 100% Diameter of A_1 ------------ 85%

Number of Grains Across Specimen : (.85 x 123) ------------ 104.5

CALCULATIONS INVOLVED IN DATA: (con'td)

(From Table No. 2 - Left Hand Edge of Photomicrograph)

Number of Grains per inch of Photomicrograph:

Average number of grains counted ------------------------------ 25.25

Distance on Photomicrograph over which grains counted -------- 12 in.

Number of Grains per inch : (25.25 / 12) ----------------- 2.10

Reduction in Grain Size:

Number of Grains per inch of Specimen A_1 -------------------- 2.10

Number of Grains per inch of Specimen A_3 -------------------- 2.73

Reduction in Grain Size : (100 - 2.10 / 2.73) -------------- 23.0%

(Calculations for Tables No. 3 and No. 4 involve same outline as Table No. 1.)

The following discussion of cold-work phenomena, grain movements, plastic deformation, elastic deformation, possible structure of grain boundaries, effect of reduction of area upon hardness, and the amorphous cement theory are a compilation of theories and observed facts by recognized authorities in the field of metallurgy and metallography. They will be presented almost entirely verbatim. It is thought that this will accomplish a ready reference upon the above mentioned subjects without making it necessary to locate the books from which they are taken. In the conclusion and summary of the thesis, the facts and theories enumerated in this section will as much as possible be correlated with the observed facts taken from the research work discussed in Part one.

"Cold Working", as defined by the Metals Handbook[3], "is the permanent deformation of a metal below its recrystallization temperature". Since the lowest limit of the recrystallization temperature is about 450° Cent., some have stated that this definition does not really define cold-working. A definition suggested by some states that it is a deformation of a metal at room or surrounding temperature.

Sauveur[4], in his book of Metallography and Heat Treatment of Iron and Steel, states of cold-working: "By cold working of steel is meant in these pages, working it while its temperature is below its critical range. The effect of cold working upon the properties of the metal is very different from that of hot working. This should not be a cause for surprise if it be borne in mind that steel above its critical range is in a condition totally different from its condition below it. Above the critical range, we have an aggregate of pearlite and ferrite (or cementite). The solid solution existing above the range will crystallize if allowed to cool undisturbedly and it has been shown that working in this range, i.e., hot working, is effective in preventing or at least retarding this crystallization, thus imparting a smaller grain to the metal. The aggregate existing below the range, on the contrary, exhibits no tendency to crystallize during slow and undisturbed cooling, because this aggregate was formed and fully developed while passing through the range, the size of its elements, that is its coarseness, depending (1) upon the coarsness of the solid solution immediately before its transformation and (2) upon the time occupied in cooling through the range. Working this aggregate, therefore, as it cools to room temperature, or working it while at room temperature, i.e., cold working it, results in distortion the existing structure, chiefly through the stretching or elongation of its crystalline elements (free ferrite, free cementite, or pearlite) in the direction of the forging, and such distortion in turn means decreased ductility and eventually extreme brittleness. The ferrite present in the aggregate, distorted by work below the critical range, may recrystallize provided the cold work ceases above its recrystallization temperature, the lowest limit of which is at about 450 deg. C. The distorted pearlite particles, however, remain distorted. While the structural distortion caused by cold working is very slight near the critical range of the metal, it rapidly increases as the temperature decreases, becoming very pronounced at room temperature. The manufacture of wire by cold-drawing affords a familiar instance of the effect of work performed at atmospheric temperature both on the stru structure and properties of the metal. It is well known that after the wire has been passed through several dies it becomes so brittle that annealing is necessary in order to make further reduction in size possible, the annealing operation removing the structural distortion and brittleness produced by working at room temperature."

Sauveur further states that "the elastic limit, tensile strength, and hardness are increased in a marked degree by cold-working, while the ductility as represented both by elongation and reduction of area is reduced, brittleness

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Sauveur further states that "the elastic limit, tensile strength, and hardness are increased in a marked degree by cold-working, while the ductility as represented both by elongation and reduction of area is reduced, brittleness

being eventually produced."

A further disucssion on the effects of cold working is entered by Jeffries and Archer[5]: "It is now known that cold deformation produces refinement of grain in the sense that one original grain, after cold work, exhibits a mixture of orientations. This type of grain refinement is not the same as the refinement of grain produced by annealing at low temperatures. For example, a metal may be obtained with the same hardness by moderately cold working a coarse-grained piece or by annealing a severely worked piece at a temperature which will produce small unstrained grains. Even though there is refinement of grain by cold working, the directional properties of the crystals are never obliterated, and, in fact, extreme conditions of cold work actually produce directional characteristics, namely a tendency for the crystal units to be oriented in a certain manner with reference to the direction of deformation."

"The general effect of cold deformation is to increase hardness and decrease plasticity. Impurities also affect the shape of grains. Non-metallic impurities generally obstruct grain growth and, because of their distribution in worked metals, the obstruction to growth at right angle to the direction of working is greater than the destruction to growth in the direction of working."

With reference to increased hardness resulting from cold working, Sauver[6] remarks: "The increased hardness resulting from cold work deformation has been ascribed to (1) grain deformation and fragmentation increasing resistance to slip, (2) distorted space lattice and (3) presence of amorphous cement at the slip planes. Rosehains modified theory postulates the existence of what he terms irregular meterial instead ofamorphous material, the former having its atoms arranged otherwise than in the regular fashion of the crystal lattice. He further believes that the presence of this irregular material plays only an indirect role in the hardening phenomenon. The material is itself incapable of crystalline slip and its location at the places where slips have occurred in cold working prevents the distorted lattice to return to its original shape after release of stress, hence the resulting hardness. Rosenhain considers lattice distortion to be the primary cause of strain hardening."

Jeffries and Archer[7] point out the following facts regarding the properties and structure of cold-worked metal. "When metals are tested at temperatures well below that of recrystallization, the passing of the elastic limit represents the beginning of plastic deformation by transcrystalline slip. At temperatures near or above the recrystallization temperature, intergranular flow may take place and mark the elastic limit; the stress required varies greatly with the time of application. At the yield point, movement on slip planes is general throughout the specimen; the effect is visible on the machined surface of a test bar, which becomes dull.

"Up to the elastic limit, the metal is not permanently altered by the application of the test load. Beyond this point, however, the deformation incident to the test alters the structure and properties of the metal. Elongation, reduction of area, and tensile strength therefore depend not only on the original condition of the metal but also upon the effect of the testing operation itself. The mechanism and effects of plastic deformation must be considered in interpreting the results of tests in which the metal is plastically deformed."

A summary of the properties of cold worked metals, stated by Jeffries and Archer[8], is:

"1. Hardness and strength of a metal increase with the amount of reduction by cold work until internal failure is produced.

"2. Plasticity of a metal decreases as the amount of cold work increases.

"3. With change in temperature of test, the properties of a cold-worked metal follow those of annealed steel, any discontinuities in the properties of annealed metal being reflected in those of cold-worked metal.

"4. Elongation of a cold-worked metal increases with respect to the elongation of annealed metal, as the temperature of test decreases below the working temperature, reaching a maximum value, after which further decrease in temperature produces a rapid decrease in elongation.

"5. The hardening effects of slight or moderate deformations are greater the smaller the initial grain size of the metal."

Some types of brittleness found in low carbon steel are enumerated by Savuer[9], who says: "Since steel containing very little carbon is essentially made up of ferrite, it occasionally exhibits brittleness which must be due to a likewise occasional brittleness in ferrite, a constituent by nature soft and ductile. Stead has indicated two kinds of brittleness from which ferrite may, and occasionally does, suffer, namely (1) inter-granular brittleness, and (2) inter-crystalline or cleavage brittleness.

"By inter-granular brittleness is meant a lack of cohesion between the ferrite grains leading to ready fracture under showk, the line of fracture following the boundary lines of the grains. Such brittleness is usually due to the presence of impurities forming brittle and more or less continuous membranes surrounding the grains. The presence of much phosphorous, however, appears to produce inter-granular brittleness without producing surrounding membranes.

"Inter-crystalline or cleavage brittleness is caused by the ferrite grains assuming nearly the same crystalline orientation so the plane of fracture follows the cleavage planes and passes from grain to grain almost in a straight line."

In an article published by Hayes and Burns[10], these authors that in reduction of area (cold) upon cold-worked steel distorted or elongated the grains to a noticeable degree when there had been a reduction of 20%; the distortion was very pronounced with 30% reduction in area.

In commenting upon the structure of cold-worked metal, Jeffries and Archer[11] state that "the most apparent distinction in crystalline grains is perhaps between equi-axed and elongated grains. In this connection, it must be remembered that the elongated grains of cold-worked metal are, in reality, aggregates of very small grain fragments."

If there has been an accompanying grain movement in the plastic deformation of the cold-worked metal in question, the following references will indicate theories that have been advanced to explain how and when this phenomenon takes place.

The following is a brief outline as presented by Howe[12], in his "Recapitulation of Movements":

- Movements
  - Fluid
  - Block
    - Non-crystalline
      - Intergranular
      - Movement of irregular grain fragments
    - Crystalline
      - Slip
      - Twinning

In distinguishing between Fluid and Block Movement, Howe[13] offers:

"Sharply distinguished from fluid movements are what might be called block movements, that is the movements of whole blocks, the parts of each which retain their relative position during the motion, as the parts of the earth retain theirs during its rotation. Such motion is like that of a book pulled out from a full shelf, a card from a pack, or a brick from an imaginary wall laid with asphalt."

Howe[14] further states: "Block movements may be in turn crystalline or non-crystalline. For though the crystalline structure of metals may well lead to strictly crystalline movements, that is to movements along definite crystallographic planes, yet it is compatible with movement along random surfaces, as the rupture of a masonry mass may avoid its joints.

"For instance, when a mass of low-carbon steel is deformed plastically, certain of its grains may slide past each other so that their boundaries form a pattern on its surface, in which case the movement is intergranular. Or as when half a pack of cards slips past the other half along the bounding faces of two adjoining cards, the faces of each individual block which moves past its neighbors within any one grain may consist of definite parallel crystalline planes, in which case the motion is by slip. Or the particles which compose certain of the blocks, while retaining their relative distances from each other, may all rotate through a definite angle, as when the slats of a Venetian blind are turned, in which case the movement is by rotation. If this rotation is through such an angle that the new position is symmetrical with the old, this rotation is called twinning. Cases of such rotation in metals are very common, and are referred to twinning, though strict proof of this symmetry has not yet been given.

"Yet in spite of the crystalline organization which slip and twinning imply, deformation and rupture might avoid these crystalline planes, and be wholly irregular, or if regular they might have the regularity only of the lines of surf on a flat beach or of a mackerel sky. They need not be either strictly straight or strictly parallel, and they need not correspond closely if at all to any definite crystalline planes. In this case the block movement is noncrystalline.

"Not only may these four types of block movement be superposed, but they may be accompanied by fluid movement. That is to say, even if the major part of each of two slices moving past each other remains a crystalline block, and moves like the muntins and panes of one sash past another, yet the metal along their sliding contacts may become decrystallized and revert to the amorphous state."

Another correlation of movements is attempted by the same author, who says, "These block movements, whether superposed or single, because they occur in a sense independently in the various crystalline grains, may integrate into what, if viewed on a large scale, is equivalent to fluid movement, quite as in the movement of a true fluid we may conceive that the atoms in a given molecule do not change their relative position, so that here movement which is of the block type as regards the atoms within the molecule, that is on the atomic scale, integrates into movement which is fluid when seen on a molecular scale. Every molecule moves relatively to all its neighbors, but the atoms move relatively only to their neighbors in other molecules, retaining their relation to the other atoms in their own molecule unchanged, or at least unaffected by motion which the fluid as a whole undergoes.

"Fluid movements are habitually rotary, as in the swirl of water. Intergranular movements too might be rotary, in the sense that one grain as a whole might rotate relatively to one or more of its neighbors. The trans-crystalline movement by twinning is rotary through a fixed angle."

An interesting theory relative to the moving of grains in the process of deformation is that of "Intercrystalline Slip", presented by Jeffries and Archer:[15] "If a piece of ductile metal is polished and etched to bring out the grain boundaries, and is then subjected to a load which causes a slight permanent deformation, examination under the microscope reveals systems of parallel lines running across the grains. In any one grain the lines are approximately straight and parallel to one another, but their direction is different in different grains. In the first stages of deformation only a few of these lines appear, and not in every grain. As the deformation increases, more lines appear, becoming closer together and appearing in grains previously free from them. Finally, other sets of lines are developed, parallel to one another in any one grain and crossing the first set of lines. Close examination shows that the first sets of lines have been displaced along the second sets by a minute amount, so that they no longer register exactly.

"The nature of these lines has been very carefully investigated by Howe, and they are known to represent block movement or slip along crystallographic planes. The lines observed are steps on the polished surface produced by the elevation or depression of blocks or fragments of the grains."

Howe[16] attempts to define and explain the mechanism of "Slip".

"Here a difficulty in nomenclature arise. The name "slip bands" if firmly attached to certain lines which deformation develops on a previously polished surface. Here "slip" naturally implies translation without rotation, so that the very name "slip" with reference to "slip Bands" itself begs the question as to the nature of the thing named, a question to which we are now going to seek to answer. If we use the name "slip bands" and thus acquiesce in this begging, we thereby embarrass the discussion, especially if we call this vectorial translation "slip". Osmond tried to avoid the entanglement by calling these lines "lines of translation." Translation might include all the six forms of movement except twinning; slip bands are improper till slip has been proved.

"Slip, when combined with the rotation of a given grain as a whole, may be likened to the movement of a book pulled out from within a row which is meanwhile tipping over. As it slides forward, the book as a crystalline block slips within the row of books. But as they all tip simultaneously, its orientation remains uniform with that of the other books on that shelf, and it leaves certainly retain a common orientation, while the book itself tips and while the row of books as a whole is rotating relatively to the books on the other shelves. In what follows it is most convenient to proceed as if the plastic deformation occurred by crystalline slip alone, and later to ask how far twinning and rotary or fluid movement may replace this slip."

In "Similies to Explain the Mechanism of Slip", Howe[17] says: "We may condeive the cement joints in a thick brickwork mass replaced by wax guides with limited shearing strength, so that under strong pressure any row of bricks can slip past any other and thereby shear across a series of wax guides normal to this movement, while it is yet held as by irresistible magnetization so that it can neither rotate nor deflect. The guide can be sheared across; it can move with the bricks in any direction as long as it remained parrallel to its initial direction; but from that direction neither the guide nor the brick which it guides can turn.

"The passing of the elastic limit means that the stress reaches such intensity that certain crystalline slices, forming part of certain crystalline grains, start to slide along the slip planes over the similar neighboring slices in those same grains.

"An alternative mechanism of slip after Osmond and Cartaud substitutes what is in effect incomplete twinning, a rocking or rotating of the units which compose each of the slices of metal involved in the movement, each unity about its right-hand side, together with a lifting of each unit by its own rocking and by that of those at its right."

Further, Jeffries and Archer[18] attempts to explain the conditions at slip planes:

"The properties of cold-worked metals and the phenomena of plastic deformation indicate that important changes may take place on the surfaces of slip during and after deformation. A number of propositions regarding the conditions at slip planes are herewith presented. For the purposes of this discussion, the term "slip plane strength" will be useful to denote the resistance to motion along a slip plane after slip has started. "Crystal strength" means the shearing strength of the unbroken crystal on planes parallel to the slip plane under consideration; it is the resistance to motion on the slip plane, <u>before</u> slip starts.

"(1) <u>Immediately after slip begins; the slip plane strength is less than the crystal strength.</u> In coarse-grained metals, slips are readily observed which have extended for a distance of several thousand atom diameters. In single crystals tested in tension, the extent of the motion on individual slip planes is still greater. After slip has once started, therefore, the resistance to further motion on the same plane must, for a while, be less than the resistance to the starting of slip on a parallel plane and hence less than the original shearing strength of the crystal. When iron has been recently overstrained, the application of very small stresses results in permanent deformation which must take place by motion on the slip planes formed in the first overstraining process. Resistance to motion on these planes must, therefore, be quite low as compared with their original strength. The same is true of brass or other metals whose elastic limit is decreased by overstraining.

"(2) As slip continues, the slip plane strength increases to a value which may be greater than the crystal strength. It is a striking fact that, when single ductile crystals are tested in tension, failure does not occur on the first slip plane. Motion continues for a certain distance, after which further deformation takes place by slip on other planes. This means that the resistance to motion on the original slip plane must have increased to a value somewhat greater than the resistance to motion on parallel planes in the crystal. The process of slip may be termed "self-stopping."

"(3) In a metal composed of an aggregate of grains, slip is stopped partly by the interference of adjacent grains and partly by the resistance on the slip plane itself. In a single crystal which is ductile it is necessary that motion continue on the first slip plane until the resistance to motion automatically becomes greater than that in the unbroken crystal. In an aggregate composed of many grains, however, motion on a slip plane in any one grain is opposed by adjacent grains through which there are no corresponding planes of weakness. Slip may there be brought to a halt by end resistance before sufficient motion has taken place to increase the resistance on the plane to the self-stopping point.

"(4) Slip planes in all stages of their history are present in cold-worked metals. Since the slip plane strength increases with motion along the plane and since the extent of the motion on the various slip planes is different according to the various conditions of external support, it is evident that the resistance to motion on the various slip planes after deformation stops may be anything from the minimum to the maximum obtainable.

"(5) Slip causes rupture of the atomic bonds on the slip plane, and immediately after motion has stopped there is only partial reestablishment of cohesion.

"(6) When the registry of the displaced crystal fragments permits, cohesion is reestablished by the fragments joining into larger crystalline units. The slip plane then disappears as such, being replaced by a potential slip plane whose strength is equal to the crystal strength.

"(7) As a rule, the crystal fragments do not register after deformation, and all degrees of disregistry occur. It has been shown by X-ray analysis that new orientations are created by plastic deformation. Consequently, there must be many, probably a large majority, of crystal fragments whose orientations do not permit them to unite except by the process of grain growth.

"(8) Reestablishment of cohesion between crystal fragments of different orientations must be attended with various degrees of disorganization as regards the arrangement of the atoms at the slip plane.

"(9) The metal of partly disorganized structure simulates an amorphous material in its mechanical properties. The characteristic properties of typical amorphous materials are, first, the great influence of time upon deformation, and second, the rapid change in properties with change in temperature. Cold-worked metals behave as though the resistance to motion on the slip planes varies in a similar manner with the time and temperature. The slip plane strength increases on cooling and decreases on heating at a more rapid rate than does the crystal strength. For example, the tensile strength of cold-worked iron increases on cooling much more rapidly than the tensile strength of annealed iron.

"(10) Atomic rearrangement on slip planes takes place at temperatures much lower than are usually associated with recrystallization. During the spontaneous

aging of overstrained iron at ordinary temperature, or the rapid recovery of elasticity at a blue heat, the slip plane strength increases so that small stresses no longer produce permanent deformations. This increase in slip plane strength, or "healing", as it may be called, may consist in the growing together of fragments of sufficiently similar orientation, or in the establishment of cohesion at additional places on the planes between fragments that do not register. Rosenhain has observed that, when a piece of iron is polished immediately after overstrain, lines are found which probably represent the intersection of the polished plane of the specimen with the surfaces of slip. These line (called X-bands by Howe) are not found in the specimen if permitted to rest or recover before polishing. Lee has reported that the recovery of iron or mild steel from overstrain is accompanied by an increase in density. All evidence is to the effect that the healing process involves an increase in the continuity of the metal. Although the electrical conductivity of metals is decreased by cold working and is, in general, least when the metal is in its hardest condition, it is to be expected that the hardening of a cold-worked metal like iron by aging or heating at low temperatures would be accompanied by an increase in conductivity."

There has been much conjecture as to the presence of amorphous material in the grain boundaries. Some noted metallurgists disprove this theory and offer an alternative theory stating that the grain boundaries must contain disoranized metal. The arguments are herewith presented.

Jeffries and Archer[19] designate crystalline materials as follows:

"Crystalline materials are characterized by the orderly arrangement of their constituent particles, i.e., atoms or molecules in definite geometrical patterns. Materials whose molecules do not posses any such regularity of arrangement are amorphous. The term "amorphous" is thus in the broadest sense, directly opposite to that of crystalline."

Sauveur[20] contemplates the existence of an amorphous cement holding the grains together: "It is believed by Rosenhain and Ewen that the amorphous films cementing together the crystalline grains of pure metals act as a vehicle for crystal growth under suitable temperature conditions. This intercrystalline amorphous cement might play the part ascribed to eutectic films in Ewing and Rosenhain's earlier theory. While according to the former theory the grains of strictly pure metals could not grow on annealing, even after straining, owing the absence of eutectic films, the amorphous cement theory permits such growth, and this is in better harmony with observed facts,

"Any annealing of cold worked metal should result in the transformation of some of the strong but hard and brittle cement resulting from cold working, into crystallized metal, and this should be accompanied by decreased hardness and increased ductility, thus accounting for the well-known influence of annealing on cold worked metal. The effect of annealing cold worked metals may be also explained on the ground that it converts a mass of extremely small grain fragments, hence possessing greater resistance to slip, into relatively large equiaxed grains with decreased resistance to slip."

With due regard to the possibilities of "mixed orientation at grain boundaries", Howe[21] states: "Along the grain boundaries there is a narrow band in which the orientation is a mixture of that of the two adjoining grains, as if dendrites here interlocked, and in Humfrey's belief, a region of progressive confusion of orientation. To decide if this were true would need very precise observations directed expecially to this point."

Sauveur[22] further believes this amorphous metal to be very hard: "It is now pointed out that the regularity of atomic arrangement in crystals leads to mechanical weaknesses along certain crystallographic planes. The absence of such planes of weakness in amorphous materials leads to great hardness at low temperatures. The hardness and strength of amorphous materials in grain boundaries may be the cause of hardness produced by cold deformation. An increase in grain boundary surface must, therefore, result in an increase in hardness. This affords a ready explanation of the fact that the hardness of metals increases as the grain size becomes smaller. Carrying this idea to the extreme, Rosenhain proposed that the great hardness of hardened steel is due to the "presence of an extremely minute network of amorphous layers" surrounding the very fine grains of Alpha iron which result from the rapid transformation of Gamma iron. He regarded the amorphous iron as being expecially hard in this case because of iron carbide in solution."

Savmer[23] assumes the existence of both crystalline and amorphous phases in any pure metal: "Assuming the coexistence of two phases, crystalline and amorphous, in any pure metal, it is essential to bear in mind that some of their physical properties differ materially.

"According to Jeffries, the cohesion of the amorphous phase is nil at the melting point, while that of the crystalline phase is considerable. On cooling, moreover, the cohesion of the amorphous phase increases more rapidly than that of the crystalline phase, resulting in the equal cohesion of both phases at a certain temperature called by him the "equi-cohesive temperature". Since the resistance to deformation must be greater the greater the cohesion, it follows that the crystalline phase will cause greater resistance to deformation above the equi-cohesive temperature than an equal amount of the amorphous phase, while on the contrary, the amorphous phase will cause greater resistance to deformation below the equi-cohesive temperature than the same amount of the crystalline phase. It follows, in turn, from this consideration that for the same metal, a coarse-grained structure, since it contains less amorphous material, will offer greater resistance to deformation above the equi-cohesive temperature than a fine-grained metal, while on the contrary, below the cohesive temperature the fine-grained metal will be more resistant to deformation. At the equi-cohesive temperature the resistance to deformation would be the same both for the coarse-grained and fine-grained

metals, since the two phases have now the same cohesion..It is believed that the recrystallization implying grain growth will not take place until a temperature is reached at which the amorphous phase is less cohesive than the crystalline, from which it would follow that the equi-cohesive temperature must correspond to the minimum temperature at which grain growth can begin."

Jeffries and Archer[24] discourse upon Amorphous Metals:

"There must of necessity be some disorganization of the crystalline structure at the grain boundaries of metals and on most of the surfaces of slip. The degree of disorganization probably varies all the way from perfect crystallinity to the completely disorganized structure denoted by the term "vitreous amorphous." All such metal of disorganized structure simulates the vitreous amorphous materials its mechaĥical properties.

"Fluidity is the important characteristic of amorphous materials. Plastic deformation takes place by the same kind of flow as in ordinary liquids, except that at a low temperature, the viscosity is great. Whereas the strength of a crystal depends on temperature and is practically unaffected by the duration of loading, the resistance to deformation of an amorphous material not only varies rapidly with the temperature for a given rate or duration of loading, but if the temperature is constant depends entirely on the rate and duration of loading.

"In general, the relative amount of amorphous metal increases with grain refinement and with cold working. The properties which metals have at high temperature of yielding slowly under constant load is presumably due to the viscous flow of disorganized or amorphous metal at the grain boundaries. Since the amount of this disorganized or amorphous metal is greater in a fine-grained metal than in a coarse grained metal, it would be expected that the fine-grained metal would be softer at high temperatures and harder at low."

Of "Possible Structure at Grain Boundaries", Jeffries and Archer[25] offer:

"Since amorphous cement cannot be produced alone, the best evidence of amorphous metal is probably to be found in the conditions at grain boundaries. In the original statement of their intercrystalline cement hypothesis, Rosenhains and Ewen advanced the idea that the crystallization of metals takes place by the addition of crystal units containing large numbers of atoms. In the region where two crystals abut against one another--that is, at the grain boundaries-- there would have to be some metal which could not attach itself to either crystal because of being too small in amount to form crystal units. Furthermore, since the crystalline grains have different orientations, the units or blocks of one would not fit in with the blocks of the other, and interstices of irregular shape would be left which could not be filled up with other crystals no matter what their orientation. The metal remaining in these interstices must then retain the structure of the liquid--i.e., must be amorphous. This conception is no longer teneable, inasmuch as it now appears quite certain that the crystal units consist of one atom each. The actual conditions must nevertheless be very similar, in a qualitative way and on a smaller scale. Certainly, where two crystals of different orientation meet, it is not geometrically possible for all of the atoms present to have places in an undisturbed space lattice without leaving some voids.

"There are three possible conditions: (1) There are voids between the two crystals; (2) there is a zone in which some of the atoms are held in both crystal lattices, in which case the lattices would be distorted at the surface of contact; or (3) there is a zone of disorganized or amorphous metal. There is at present no known way of determining the actual structure at the grain boundaries of metals."

That some noted metallurgists are inclined to disagree with the existence of a so called "amorphous cement" is indicated in the following:[26]

"From the analogy of slow flow of amorphous materials like pitch there was built up, a couple of decades ago, the idea that metals contain an amorphous constituent. It was obvious that the crystalline grain could not be amorphous; so it was postulated that a submicroscopic boundary layer of "cement" about the grain or crystal is amorphous. While the more cautious early advocates of the amorphous theory were careful to phrase their comments to the effect that the boundary material acted as though it were amorphous, others were less hesitant and fell into calling it actually amorphous. Several studies have indicated the boundary material is essentially crystalline. Layers of sputtered metal only a few atoms thick have been prepared which appeared structureless when examined by X-rays but which shifted over to crystalline form on very slight heating. Recent work, however, indicates that the advocates of amorphous metal are in a defensive position."

Permanent deformation of a metal involves a displacement within the material, during which the cohesion is overcome between the parts undergoing relative displacement. The property of plasticity therefore means that the displaced parts must reestablish cohesion in their new places. Howe[27] differentiates between Elastic and Plastic Deformation thus:

"Stress within the elastic limit causes elastic deformation, from which the metal recovers its size and shape exactly, after the release of the stress. Stress beyond the elastic limit continues to increase the elastic deformation, and apparently at the same rate as before, but adds plastic deformation to it. On the release of the stress the metal recovers from so much of the existing deformation as is elastic but retains that which is plastic. Thus we recognize the plastic deformation as permanent set. "Plastic Deformation" in the cold is identical with cold work and overstrain. Stress pushed far enough beyond the elastic limit causes rupture."

Jeffries[28] and Archer further point out that "When the external shape of a piece of metal is changed by a deforming load, the shapes of the grains undergo similar changes. Normally, the grains are so shaped that, on the average, their diameters are equal in all directions. Such grains are called equi-axed grains. Now if the metal is deformed, as by drawing out into a wire, the grains are similarly drawn out. The change in the external shape of a grain is made up of a multitude of minute slips, each so small that the grain retains an apparently smooth outline. Lines visible within the grains are undoubtedly due to cold deformation. Rosenhain considers these to be the traces of slip planes on the plane of the micro-section. Howe is less certain of their nature, and calls them "X-Bands".

"The changes which occur in the structure of the metal when it is plastically deformed will be described briefly.[29] They are:

"1. Slip takes place on the glide planes, spaced many atoms apart.

"2. With continued cold work, the grain fragments are oriented in a definite direction.

"3. As slip progresses shear resistance to further slipping on these planes increases.

"4. The mechanism of plastic flow appears to be one of block displacement, by rotation and translation.

"5. The "blocks" are fragments of grains and become smaller and smaller as the cold working is continued, but the blocks retain their identity even after the severest plastic deformation.

"6. The "blocks" are fragments of grains, particles of varying dimensions, some being colloidal. X-ray and electron diffraction studies prove that the lattice dimensions as well as the cubical symmetry is changed slightly as the particle size within the displaced blocks becomes smaller and smaller.

"7. The density of the metal is decreased due to an increase in spacing between the displaced blocks (X-ray method can detect this).

"8. The particles within the blocks tend to roughen the glide surface, and resistance to further slipping is increased, with the result that the metal hardens and its ductility is lowered. (The blocks referred to in this discussion is as used in block displacement)."

The general summary included in this section is derived from the research work discussed in Section One; that is, from the metallographic study of the three sections of steel analyzed. The correlation of this summary with the theories and facts advanced by various authorities in the field of metallurgy and metallography (from Section Two) then make it possible to draw certain conclusions relative to the cold-worked steel in question.

GENERAL SUMMARY OF THE THREE SECTIONS

The following facts are now enumerated to summarize briefly the research work for the three sections of steel:

1. Though each section is a different piece of metal, a reduction in area was noted from one end of each section to the other, the reduction in Section "E" being approximately twice the value for each of the other sections.

2. Section "A" and section "E" gave indications of both "ghost lines" or ferrite strips and "killed steel", while this quality was not noticed in Section "B".

3. Cementite or what appeared to be cementite occurred in all three sections, appearing in the grain boundaries. It was more noticeable in Sections "B" and "E", than in Section "A". This occurrence was in the form of strips near pearlite, in sections devoid of pearlite, and in the shape of "divorced" cementite.

4. The hardness values as determined by the Rockwell Hardness Tester agreed within 10 points Rockwell B (on the average) from end to end of the three sections. The hardest points occurred at the points of bending. There was therefore in these sections (1) no increase in hardnessdue to decrease in area, and (2) no increase in hardness resulting from elongation of grains.

5. The reduction in grain size was about the same for Sections "A" and "E", in the neighborhood of 30%. Section "B", as analyzed, exhibited a maximum reduction of about 8%. These values were found by counting the number of grains across the diameters of each specimen.

6. Grain fragmentation or what is believed to be conclusive evidence of the phenomenon, was found in each section.

7. The reduction in grain size did not appear to increase or decrease regularly with the reduction in area encountered.

8. Distortion to a marked degree was found in Figures No. 55 and 56, where the greatest reduction in area was noted. The most distortion found was at the point of bending in Specimen E_3.

CONCLUSIONS

1. With reduction in area from cold-working, there was no increase in hardness, a fact contrary to theories advanced.

2. With reduction in area from cold-working, there was a decrease in grain size. Since decreased grain size is supposed to increase grain boundaries and consequently, the amount of amorphous cementing material in the grain boundaries (if such a constituent does exist), there should be an accompanying increase in hardness. Such was not the case, at least as shown by the Rockwell Tester.

3. The points of greatest hardness were at the places where bends in the strips were in evidence. Since there was not always an indication of elongation of grains at these points, what then must this hardness be due to?

4. The hardness from end to end of each of the three sections analyzed agreed very closely. Thus cold working has not increased hardness or brittleness in this instance.

5. Low-carbon steel is supposed to be very ductile, a factor important in the cold-working phenomena. Since there appeared (up to a reduction in area of about 20%) no regular indications of grain elongation, and since there did appear to be many indications of grain fragmentation, it would seem, within these limits, that the elastic limit of the grains had not been exceeded, even though the entire section had itself been plastically deformed. Thus the tremendous pressure of the dies used in cold-working had served to crack the grains. Or is this fragmentation possibly due to what is known as characteristic Ferrite Brittleness?

6. There must have been a movement of grains in the metal, for how else could there have been a reduction of area in each section? Is it possible that rolling characteristics of the hot-working preliminary to cold-working effected this?

7. There were definite indications of the presence of cementite in the grain boundaries at points devoid of Pearlite. Where did this cementite come from? Indications here would seem to show that the presence of this constituent in the grain boundaries did not serve to make the metal harder.

8. Since cementite has been found in the grain boundaries, this substantiates the belief that grain boundaries consist of at least some crystalline material; whether amorphous material is also present is beyond comprehension.

9. The grains begin to be noticeablely distorted at the point where a reduction in area of 30% occurs. This is in agreement with the recent work of Hayes and Burns.[10]

10. The size of the grains was reduced considerably. This would enchanee the formation of more and new grain boundaries. Where does this grain boundary metal come from? Did the grain fragmentation produce this material, or is there a void between grains? Or is it possible that a difference in orientation has produced this phenomenon? To go on, with increased grain boundaries, there

should be more disorganized metal or perhaps amorphous materials. This should increase the resistance to slip. With increased resistance to slip there should be increased hardness. This was not the case in this investigation.

11. That the hardness has not increased with (1) reduction in area, (2) decrease in grain size, and (3) increase in so-called amorphous cement in grain boundaries, would seem to disprove, in this instance, that there is any amorphous constituent in the grain boundaries, a fact contrary to theories advanced. Even at the points where distortion was evident, there still did not seem to be an increase in hardness.

That the conclusions stated above are not in harmony with previously stated facts and theories advanced by noted metallurgists and metallographers, is quite evident. Not only that, but the experimental evidence itself seems to formulate conclusions which are in some cases contradictory to each other. For instance, the strip of steel exhibited a reduction in area from one end to the other. Yet the hardness and elongation of grain structure that is supposed to accompany this reduction was not in evidence. The grains themselves were fragmented in many instances and decreased in size with reduction in area. Yet this reduction in grain size was not gradual or regular to any appreciable degree. The strips of metal were plastically deformed, yet the grains, which are supposed to be the fundamental units in the steel, were not elongated. Shouldn't they have been stretched with this narrowing-out of the metal and consequently a movement of grains? Even where elongation was in evidence, in Section "E", the hardness did not increase with respect to the hardness exhibited at other points. Low-carbon steel is supposed to be ductile and with the accompanying reduction in area to support this fact, the fragmentation of the grains in the metal then appeared to contradict it.

These statements lead us to the always pertinent question: Are we really viewing the true grain structure of metal under a microscope? Does the etching solution reveal the true structure or are we merely scratching the surface? In the cold-worked steel herein discussed, there has been a reduction in area and hence a stretching or pulling out of the strip metal. Was this stretching accomplished by each one of the multitude of grains being separately stressed, elongation or fragmentation taking place? Or did the long strip stretch out as a whole piece of metal would if of fibrous structure from end to end?

A possible answer to these questions might be obtained in this manner: Carefully cut and polish a small thin section of low-carbon (ductile) and etch it in the customary manner. Next clamp it in a small machine designed to stress the metal, being accomplished by means of heavy gears so constructed that the specimen will be slowly and steadily stretched or elongated; that is, pulling on the two ends of the metal much as one would stretch a rubber band. While this stress is occurring, view the specimen thru a microscope and if possible, take motion pictures of the phenomena. If the etched grain structure retains its characteristic position and moves as individual blocks that are being elongated, it is definite proof that we are viewing true grain structure, and not a surface phenomena. If, on the other hand, the ferrite and pearlite seem to smear over each other and pull out to destroy the grain structure, thus leaving an irregular, jumbled mass, then the metal is evidently being stretched as one large complete unit. Then our conceptions of grain structure and supposed grain movements would receive a tremendous setback.

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SECTION II.

AN INVESTIGATION OF TUBE FAILURE IN 1400 lb. BOILER

INTRODUCTION

The following report is an investigation of a tube failure in the water walls of a 1400 pound pressure boiler installed at the Firestone Tire and Rubber Co., Akron Ohio.

A letter from W. K. Adkins, Power Engineer of the Firestone Tire and Rubber Co. is herein included. This letter states the specific conditions under which the tube failure occurred.

A second letter states that the results obtained agreed with work done by others upon the same failure.

It is thought that this investigation well illustrates the application of metallographic theory to a practical end in industry.

Akron, Ohio.
February, 18, 1937.

Mr. C. L. Crandall,
Department of Chemical Engineering,
Michigan State College,
East Lansing, Michigan.

Dear Mr. Crandall:

This will acknowledge receipt of your letter dated February 15 relative to your recent interview and to the tube failure in our 1400 lb. boiler.

We are sending you, under separate cover a small section, at the point of failure, from the side wall tube which failed in our high pressure boiler the early part of this year. We are also sending a cross section of the sam tube at a point located two feet above the failure. Following are answers to the questions in the last paragraph of your letter.

1) The boiler had been operating at full load for five days. It was started up Sunday evening, and failure occured Friday A.M. The boiler is normally out of service over week ends and is bottled up for periods of from twenty-four to thirty-six hours during which time the pressure drops to, from 300 to 500 lbs.

2) Failure occured in the left side wall, when facing the front of the boiler, in the twenty-seventh tube from the rear wall, and at a point sixteen feet above the lower side wall header.

3) Tubes are straight carbon steel "0" gage, and are hot seamless drawn, furnished by the Globe Steel Tube Company through Combustion Engineering Corporation.

4) Water is all condensate. We carry pH from 11 to 11.2 Total maximum dissolved solids 150 ppm of which seventy parts is sodium hydroxide, sixty parts sodium sulphate, and twenty parts sodium chloride. There is also a small amount of suspended solid which is about 50% copper and 50% ferrous hydroxide.

5) Slag accumulates on side wall tubes to a maximum thickness of from 3/8" to 1/2" which has the following analysis:

SiO_2	39.60%	Al_2O_3	16.90%	MgO	0.32%
Fe_2O_3	40.10%	CaO	4.34%	B_2O_3	57.60%

Yours very truly,

THE FIRESTONE TIRE AND RUBBER CO.

W. K. Adkins
Power Engineer

Akron, Ohio
March 31, 1937

Mr. C. L. Crandall
Department of Chemical Engineering
Michigan State College
East Lansing, Michigan

Dear Mr. Crandall:

1400# TUBE FAILURE

Wish to acknowledge receipt of your report in connection with tube failure in our 1400# boiler.

The report is very well done and the conclusions reached agree with those advanced by others.

Wish to take this opportunity to express our appreciation of the interest that you have shown in the subject.

Yours very truly,

FIRESTONE TIRE & RUBBER COMPANY

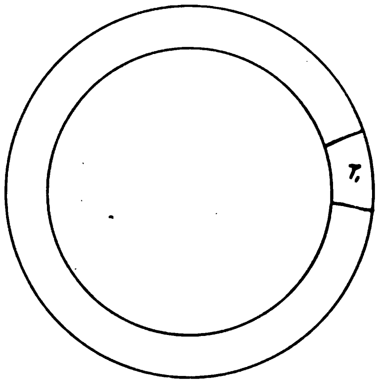
W. K. Adkins,
Power Engineer

SUMMARY OF INVESTIGATION

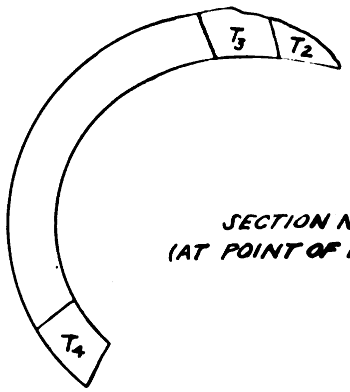
The investigation of the boiler tube failure was carried out along metallographic lines. Photomicrographs were taken of the section two feet from the failure and of that portion where failure occurred. Conclusions were reached that the failure was not due to embrittlement, decarburization, or to some primary defect in the metal.

The failure is believed to be the effect of localized overheating. The exterior surface of the tube was subjected to a temperature of near 2200° Fahr. in the combustion chamber of the furnace. The tubes are normally water cooled and thus protected from this heat which is in excess of the critical temperature of the steel. However, if a gas bubble should get entrapped next to the inside surface of the metal, or a piece of scale become adhered to it, then the boiler tube would no longer be cooled by the water at that point. In two to three minutes, the temperature of the metal would pass on into the critical range, 1500° Fahr. or higher, and the weakened steel, at red heat, would lose tensile strength due to the enormous internal pressure, and burst out suddenly to exhibit the "ballooning-out" as experienced by the tube failure. The great drop in pressure of the water bursting out of the tube into the combustion chamber would serve to cool or quench the hot metal. This statement is substantiated by photomicrographs of Specimen T_2 and T_3, where the structures exhibited show definitely that the steel was carried through the critical range and subjected to a quick quench. Thus the effect at this one point in the boiler tube might be compared to putting a piece of metal in a furnace, heating it above its critical range, and then quenching it in brine.

Figure No. 1 - Showing Location of Specimens in Each Section of the Boiler Tube. Thickness of Tube 3/8".



CROSS-SECTIONAL VIEW OF SECTION NO. 1. (2' FROM POINT OF FAILURE.)



SECTION NO. 2 (AT POINT OF FAILURE)

FIGURE NO. 1

BRIEF DISCUSSION OF METHODS OF ANALYSIS

The purpose of this discussion is to enable the reader to get a brief description of metallographic methods of analysis. Small sections or specimens were cut from two pieces of boiler tubing and were designated as in Figure No. 1. Each specimen was separately mounted in bakeolite, polished, and then etched with Nital (Nitric Acid in Methyl Alcohol); the etching reagent acts upon certain constituents of the metal to reveal the granular structure of the specimen. The entire specimen is then viewed under a microscope and pictures taken at various magnifications to reveal the typical structure possessed by the metal. From these pictures, knowing the kind of steel and the heat treatment it has undergone, the properties of the metal may be studied. The use of hardness tests also serves as an aid in the analysis, the Rockwell Hardness Tester being used in this investigation.

If the metal undergoing inspection does not appear to have uniform properties, that is, it is not in its "normal" state, due to cold or hot working, quenching, carburizing, straining, etc., then it is necessary to normalize the specimen before its properties can be determined. Tieman* describes normalizing as follows: "A form of annealing known as normalizing consists in reheating to a temperature above the critical range, holding at that temperature a certain length of time, slowly cooling finally being employed. It is commercially used to secure uniform conditions on materials treated in various ways or where, as in the case of billets, the finishing temperature and amount of working have resulted in a very coarse grain."

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* - The Metallography and Heat Treatment of Iron and Steel, Saveur, McGraw and Hill Book Co., 1935, p 211.

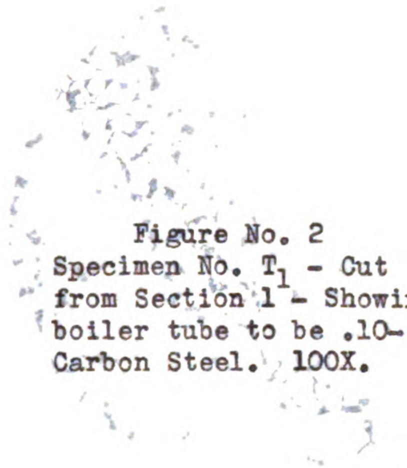


Figure No. 2
Specimen No. T_1 - Cut from Section 1 - Showing boiler tube to be .10-.15% Carbon Steel. 100X.

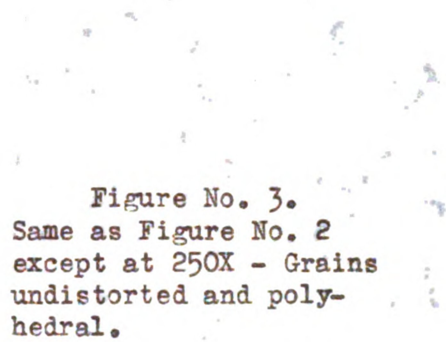


Figure No. 3.
Same as Figure No. 2 except at 250X - Grains undistorted and polyhedral.

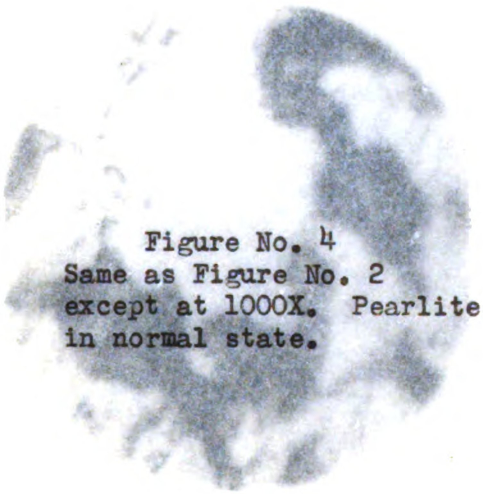


Figure No. 4
Same as Figure No. 2 except at 1000X. Pearlite in normal state.

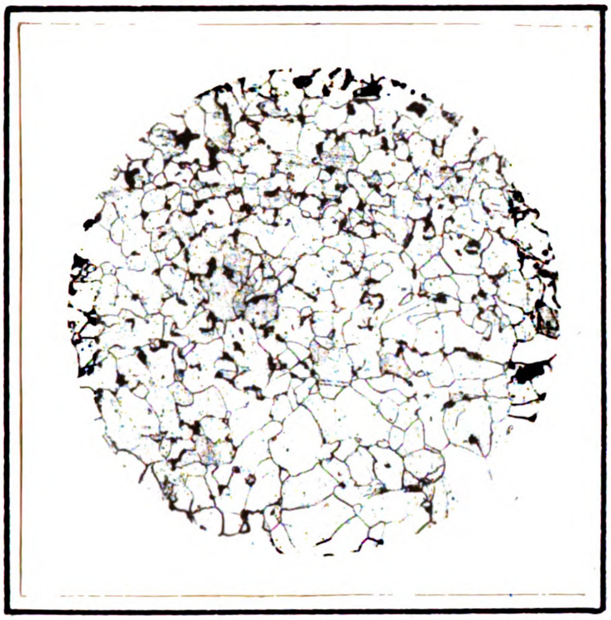
Figure No. 5
Specimen No. T_2 - Cut from Section No. 2. Showing quenched structure. 100X.

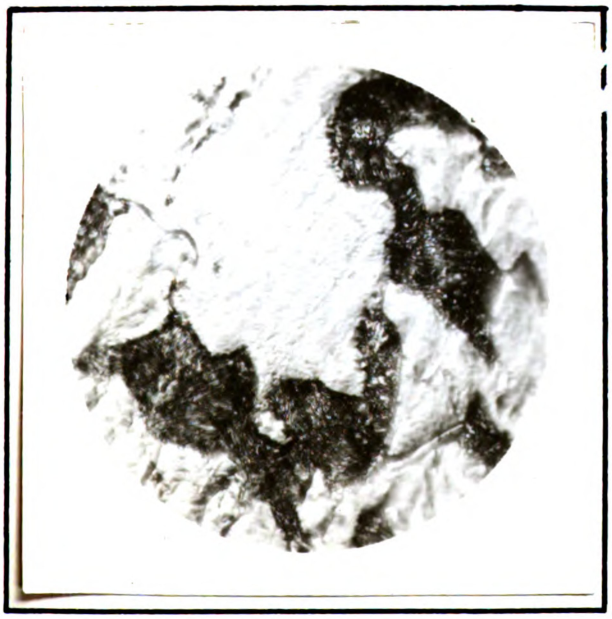
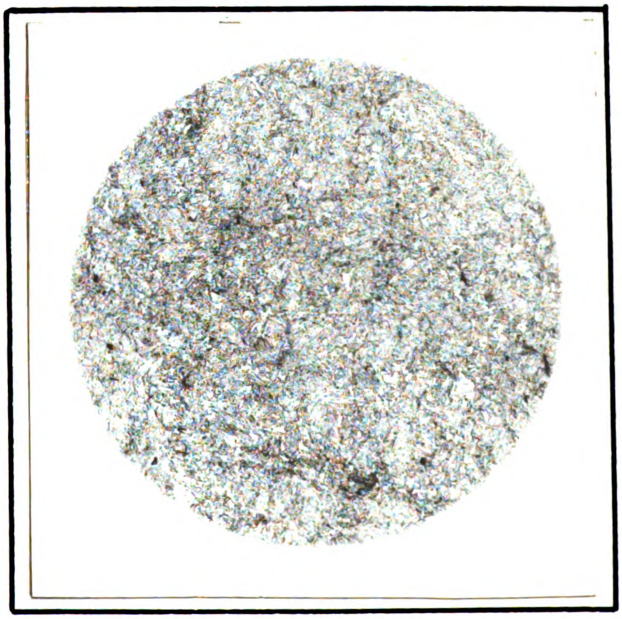
Figure No. 2
Specimen No. T_1 - Cut
from Section 1 - Showing
boiler tube to be .10-.15%
Carbon Steel. 100X.

Figure No. 3.
Same as Figure No. 2
except at 250X - Grains
undistorted and poly-
hedral.

Figure No. 4
Same as Figure No. 2
except at 1000X. Pearlite
in normal state.

Figure No. 5
Specimen No. T - Cut
from Section No. 2.
Showing quenched struct-
ure. 100X.



PROCEDURE AND DISCUSSION IN DETAIL

By combining the procedure and discussion, it is though that a more comprehensive picture can be obtained of this type of analysis. Each specimen will be discussed separately.

Specimen No. "T_1"

Figure No. 2 is a photomicrograph of Specimen T_1 taken at a magnification of 100 diameters (100X), showing a typical structure of the metal. This picture revealed that the metal was a typical low carbon steel (.10% to .15% Carbon). The larger grains of grayish cast are Ferrite (alpha iron and carbon), while the darker spots are Pearlite. Pearlite is defined as Ferrite plus Cementite (Fe_3C). Figure No. 3 is a photomicrograph of Specimen T_1 at 250X, this picture showing that the grains of metal were polyhedral and that the pearlite was in a normal state. Figure No. 4 was taken at 1000X to show the condition of the Pearlite in Specimen T_1. It was found to be in what is termed "Normal" or laminated pearlite, in which alternate dark and light bands or lanallae of ferrite and cementite appear. Summarizing, these three pictures showed the metal to be a low carbon steel in a normal state, of .10-.15% carbon, with no evidence of distortion, occlusions, etc.

Specimen No. "T_2"

Having a knowledge of the structure of the steel in the normal state before failure, it was next necessary to investigate the metal at the point of failure. Specimen T_2 was photographed in much the same manner as Specimen T_1, photomicrographs being taken at 100X and 1000X only. Figure No. 5 revealed an entirely different structure, and with the aid of Figure No. 6 at higher magnification (1000 diameters) it was found to be a needle-

Figure No. 6
Same as Figure No. 5
except at 1000X.

Figure No. 7.
Specimen No. T_3 - Cut
from Section 2. Showing
quenched structure. 100X.

Figure No. 8
Same as Figure No. 7
except at 250X.

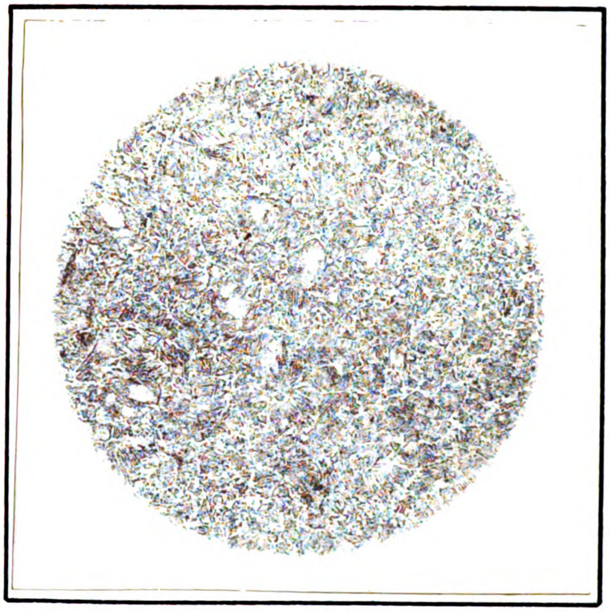
Figure No. 9
Same as figure No. 7
except at 1000X.

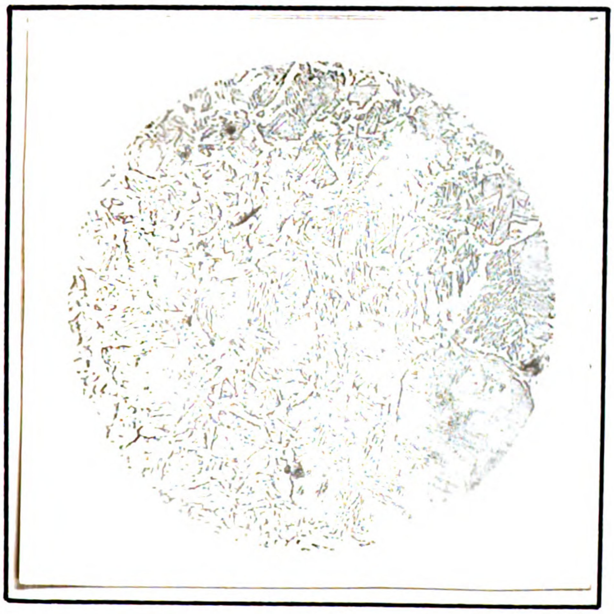
Figure No. 6
Same as Figure No. 5
except at 1000X.

Figure No. 7.
Specimen No. T - Cut
from Section 2 Showing
quenched structure. 100X.

Figure No. 8
Same as Figure No. 7
except at 250X.

Figure No. 9
Same as figure No. 7
except at 1000X.





like structure which is typical of a steel which has been heated above its critical range, 1500° Fahr. or higher, and then quenched. By critical range is meant thermal transformation points where the steel in question changes certain of its physical and chemical properties. This is in the region where the metal reaches a "red" heat. A structure of this type in steel, under the conditions named, is therefore very conclusive evidence that the metal must have been under localized heating phenomena that carried it up into the "red" heat range and that when the metal wall burst out, it must have been quenched by the enormous drop in pressure.

Specimen No. "T_3"

Photomicrographs were next taken of Specimen T_3 to determine if the steel showed the same properties as the adjacent T_2 (see Figure No. 1). Photomicrographs at 100X, 250X, and 1000X showed that the steel was still in a state where it had been carried up through the critical or "red" heat range, but had been cooled (or quenched) at a slower rate. Thus T_3, due to its location and increase in diameter was slower cooled than T_2. Figures Nos. 7, 8, and 9 show the above condition to be true.

Specimen No. "T_4"

Figures No. 10 and No. 11, taken at 100X and 250X respectively, show that Specimen T_4, taken from the same section of the tube that failed, (see Figure No. 1) but on the opposite side of the tube, is approximately of the same structure as Specimen T_1. This would indicate that the steel at the point of failure was not deficient providing Specimens No. T_2 and No. T_3 had not in some manner or other become decarburized. This decarburizing effect is discussed in the next paragraph.

Figure No. 10
Specimen No. T_4 - Cut from Section No. 2. Showing steel to be analsgous with Specimen No. T_1. 100X.

Figure No. 11
Same as Figure No. 10 except at 250X.

Figure No. 12.
Specimen No. T_2 in normalized state - heat treat at 1800° F. for 1 hr. with furnace cooled. 100X.

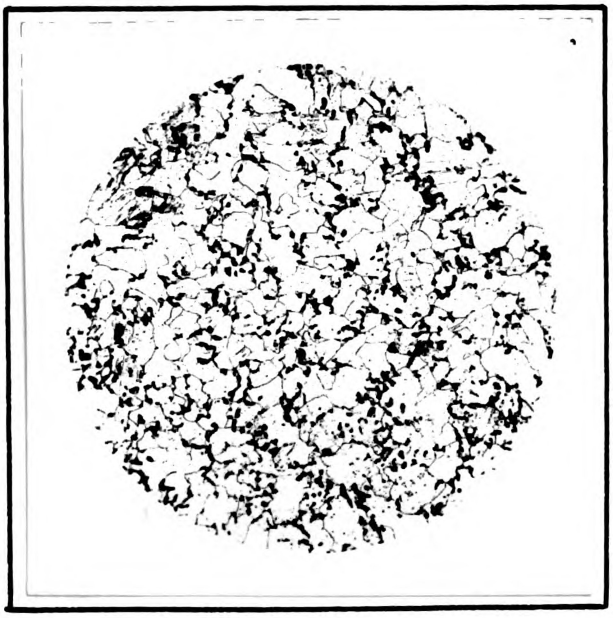
Figure No. 13.
Same as Figure No. 12. except at 250X.

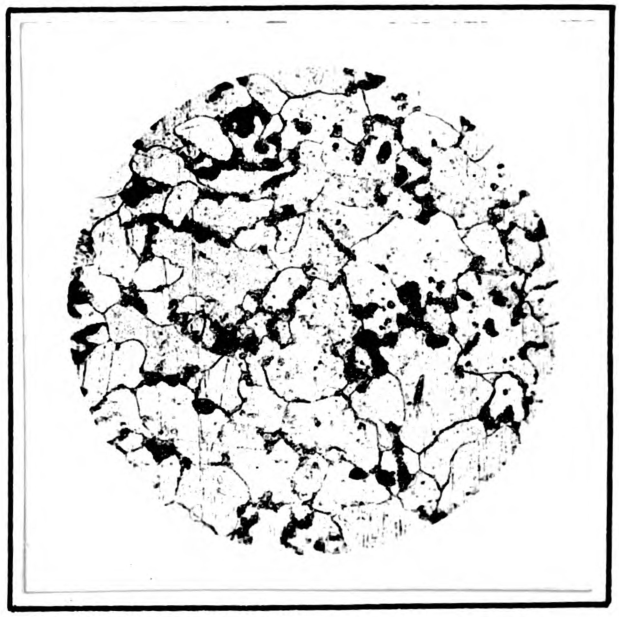
Figure No. 10
Specimen No. T_4 - Cut from Section No. 2. Showing steel to be analagous with Specimen No. T_1. 100X.

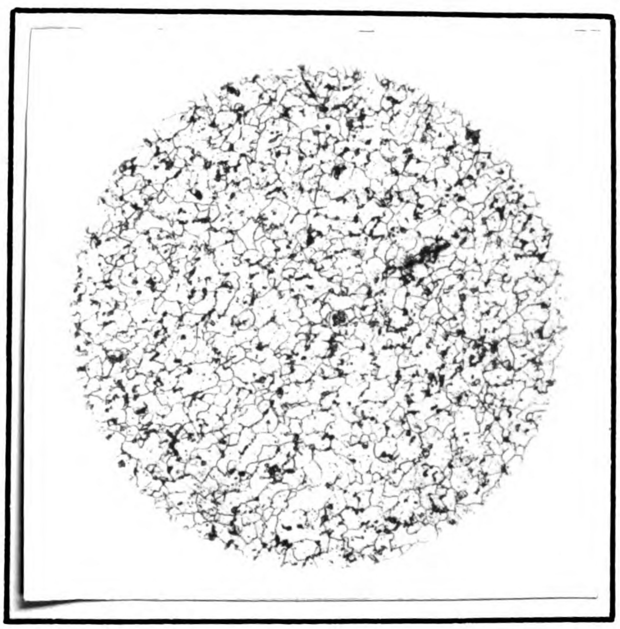
Figure No. 11
Same as Figure No. 10 except at 250X.

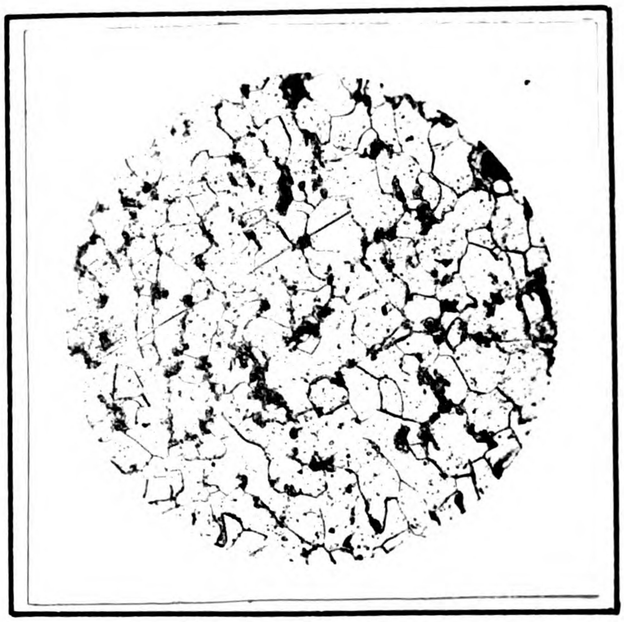
Figure No. 12.
Specimen No. T_2 in normalized state - heat treat at 1800° F. for 1 hr. with furnace cooled. 100X.

Figure No. 13.
Same as Figure No. 12. except at 250X.









Normalizing of T_2 and T_3

It is impossible to determine by metallographic methods the carbon content of steel in the quenched state, as pictured in photomicrographs No. 5 to No. 9, inclusive. To investigate the two specimens T_2 and T_3(at the point of failure) it was necessary to normalize them to ascertain if decarburization had taken place. The normalizing was accomplished by placing the specimens in a cold furnace, the temperature then being raised to 1800° Fahr., held at that temperature for one hour, and then furnace cooled. In this manner, the steel was changed from the quenched or hardened state to the normalized condition which consists of Pearlite and Ferrite. Figures No. 12 and No. 13 indicate a structure analagous to T_1 and T_4, showing that the failure was not due to decarburization; the carbon was present as expected in the form of Pearlite. Photomicrographs of T_3 in the normalized state are the same as Figures No. 12 and No. 13, and are therefore not shown.

Hardness Determinations

The Rockwell Hardness Tester was next employed in the study of the boiler tube. Steel in the normal state as evidenced in T_1 and T_4, and also in the normalized structures of T_2 and T_3 should be softer than the quenched steel in T_2 and T_3 (before normalizing). Table No. 1, under the section "Data" indicates that this statement is true, thus further proving that for this type of steel, there had been a heating through the critical range and an accompanying quench. Also, since T_2 was evidently quicker cooled than T_3, it should exhibit a higher Rockwell reading, a statement also true. The hardnesses are in Rockwell "B", and the larger the number, the harder the steel. For instance, Rockwell 89B is harder than Rockwell 60B, but softer than Rockwell 95B.

If the hardness of T_2 or T_3 had been very low, say Rockwell 30B,

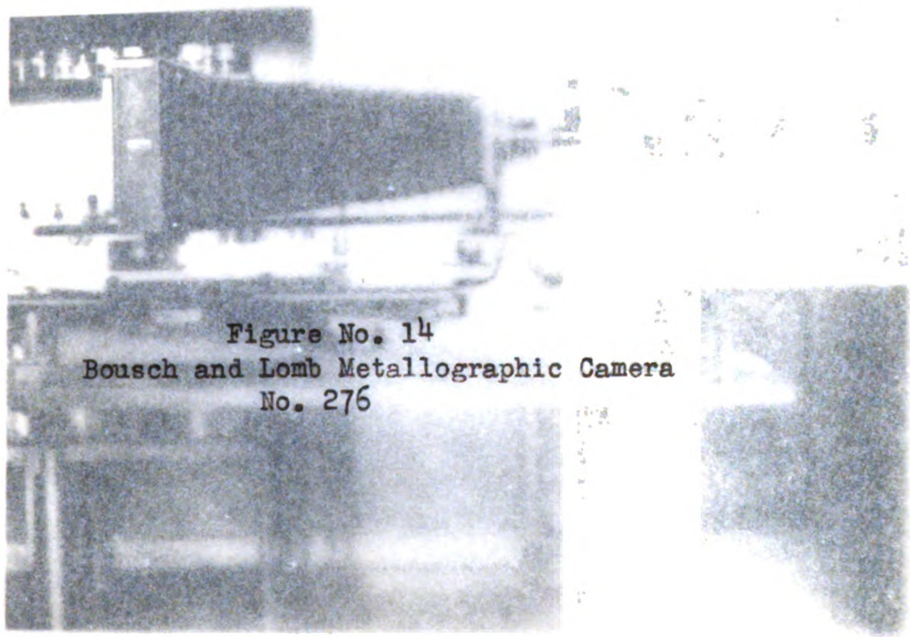
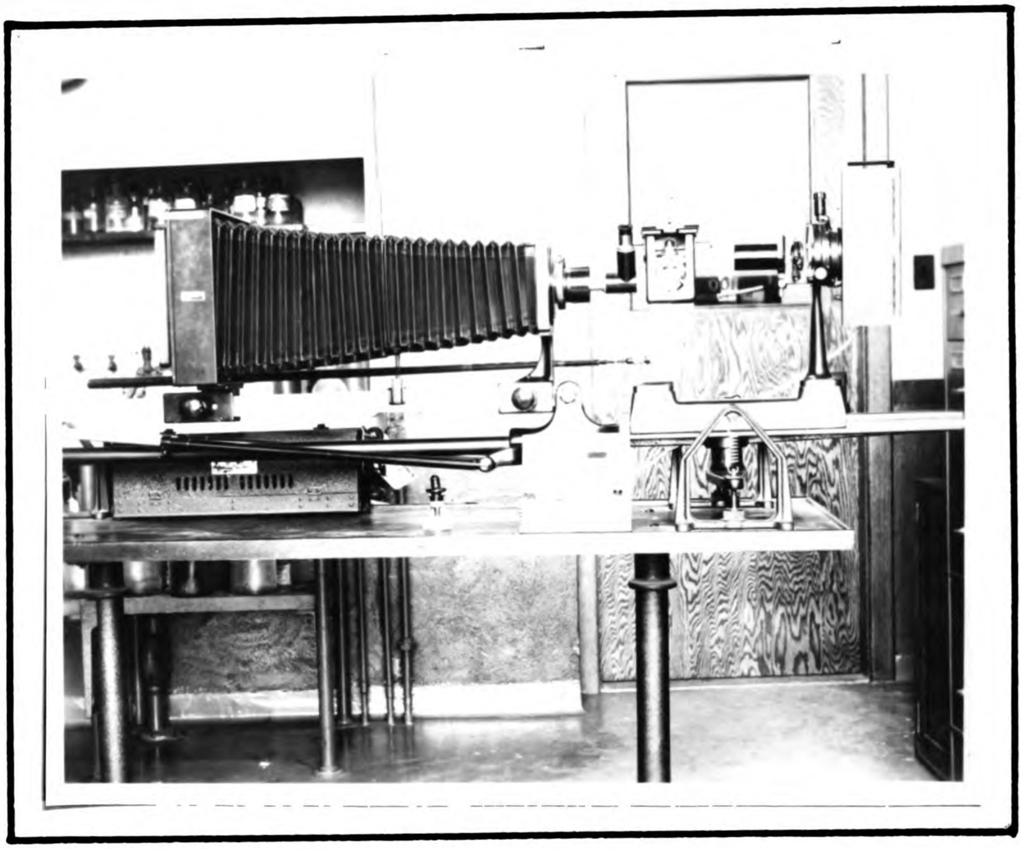


Figure No. 14
Bousch and Lomb Metallographic Camera
No. 276

Figure No. 14
Bousch and Lomb Metallographic Camera
No. 275



it would have been partial evidence that the steel had become decarburized, as hardness of steel of this type varies in proportion to the amount of carbon contained.

Failure Not Due To Embrittlement

In the opening paragraph, a statement was made that it was thought that the failure was not due to embrittlement. Embrittlement causes have been the subject of much conjecture in the past; some say that caustic is responsible for this type of failure, others claiming it is silica in the presence of caustic. However, in this tube failure, if embrittlement had been the cause, it is thought that a jagged, irregular, cracking open of the metal would be in evidence. The embrittlement would gradually pit out the metal surface, but the cooling water would always be inside the tube, thus causing the metal to finally crack open in an irregular fashion. Photomicrographic examination of this type of failure should show the metal to be in a normal state as the steel in this case would not be subjected to localized overheating into the "red heat" range. As has been stated previously, this ballooning-out effect of the boiler tube, as might be experienced by a piece of rubber under pressure, could only be accomplished with steel if it had been heated up into or above its critical range. In this range of "red heat", a decided loss in tensile strength would cause the now plastic metal to burst out as in the tube failure covered in this report.

Conclusion

The emphasis of the fact that deficient metal could not have caused this failure is again herein included. Also, consideration has been given to the fact that slag collects on the outside of the tubes to thicknesses of 3/8" to 1/2". This scale would serve as an insulator between the metal and the intense heat. Should a piece of this scale drop off the tube, it is not believed that the increased heat upon the outside surface of the metal would be sufficient to cause localized overheating, since the water would still be inside the tube at that point.

The phenomena of localized overheating was said to have been caused by an entrapped gas bubble or scale of the adherent type, thus insulating the metal from the cooling water inside of the tube. Where or how this gas bubble or scale could have occurred at this point and not at other points in the boiler is not conceivable. If scale had been the cause, it is obvious that the tremendous pressure at the time of the burst out of the tube would have carried away the scale, thus making it impossible for a positive statement that this was the factor involved. The gas bubble effect is thought less possible than the scale adherence, but such entrapment of gas in the water walls would not be absolutely impossible. It is thought that any further cause of the tube failure from this viewpoint could only be carried on in the power plant.

Data

Table No. 1 gives the hardness reading at various points on each specimen, as well as average hardnesses.

Table No. 2 is an Index of Photomicrographs taken for this paper, the pictures being taken with a Bosch and Lomb Metalloscope No. 276, shown in Figure No. 14.

Specimen No.	Hardness Readings* A	B	C	D	Average Hardness
T_1	69	65	50	60	61
T_2	99	103	100	101	101
T_3	85	89	87	89	87
T_4	49	57	58	61	56
T_2**	47	56	56	59	54
T_3**	56	62	63	63	61

* - All hardness readings in Rockwell "B".
** - Normalized structures.

TABLE NO. 1
HARDNESS DETERMINATIONS.

Figure No.	Specimen No.	Eye Piece	Objective	Bellows Length (cm)	Magnification (X)	Exposure Time
2	T_1	7.5	16 mm	27.0	100X	140 sec.
3	T_1	7.5	8 mm	34.5	250X	5 min.
4	T_1	7.5	1.8 mm	34.5	1000X	15 min.
5	T_2	7.5	16 mm	27.0	100X	140 sec.
6	T_2	7.5	1.8 mm	34.5	1000X	15 min.
7	T_3	7.5	16 mm	27.0	100X	140 sec.
8	T_3	7.5	8 mm	34.5	250X	5 min.
9	T_3	7.5	1.8 mm	34.5	1000X	15 min.
10	T_4	7.5	16 mm	27.0	100X	140 sec.
11	T_4	7.5	8 mm	34.5	250X	5 min.
12	T_2*	7.5	16 mm	27.0	100X	140 sec.
13	T_2*	7.5	8 mm	34.5	250X	5 min.

* - Normalized structure.

TABLE NO. 2
INDEX TO PHOTOMICROGRAPHS