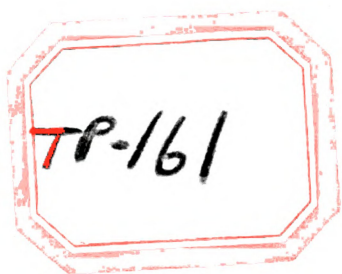


SOME FACTORS AFFECTING
RETAINED AUSTENITE IN
ALLOY STEELS

Thesis for the Degree of M. S.
MICHIGAN STATE COLLEGE
William James Buehler
1947

THESIS

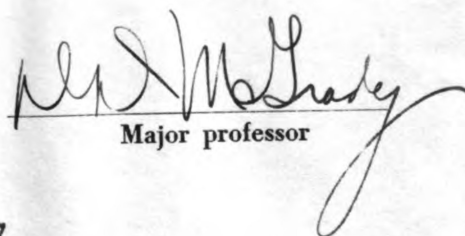


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Some Factors Affecting Retained Austenite
in Alloy Steels.

presented by
William J. Buehler

has been accepted towards fulfillment
of the requirements for
M.S. degree in Chemical and
Metallurgical
Engineering.


Major professor

Date May 29, 1947

SOME FACTORS AFFECTING
RETAINED AUSTENITE IN ALLOY STEELS

By
William James Buehler

Submitted to the School of Graduate Studies of Michigan
State College of Agriculture and Applied Science
in partial fulfillment of the requirements
for the degree of
MASTER OF SCIENCE

Department of Chemical and Metallurgical Engineering

1947

THESIS

Table of Contents

	Page
<u>Introduction</u>	3-11
<u>Experimental Procedure</u>	
Part I	12-16
Part II	16-17
Part III	18
<u>Diagrams</u>	
Carbon analysis apparatus	19
End-quenching apparatus	20
<u>Experimental Results</u>	
Outline	21
Carbon gradient data	22-26
Graphs of carbon gradients	27-31
Photomicrographs for Part I	32-57
End-quenching data	58-59
End-quenching graphs	60
Microstructure of end-quenched bars	61-63
Photomicrographs for Part II	64-69
Photomicrographs for Part III	70-72
<u>Discussion</u>	73-81
<u>Conclusions</u>	82
<u>Possible Future Work</u>	83
<u>Selected References</u>	84-86

Introduction

Solid solutions in which gamma iron is the solvent and carbon is the solute are called austenite (1). The solid solution austenite is formed by heating a steel containing between 0.03 and 1.7% carbon to the austenitizing temperature. The austenitizing temperature is a function of the amount of carbon and alloying elements present in the steel. Gamma iron is quite important because practically all heat treating is done from this solid solution range which occurs above about 1330°F. Upon rapid quenching it has been discovered that certain quantities of austenite remained untransformed in the martensitic matrix. Retained austenite is particularly undesirable from the standpoint of practically all physical properties due to the fact that it is considerably softer and more plastic than martensite.

The subject of the decomposition of austenite in steels, because of its immense practical importance, has been studied very carefully in recent years (2) (3). The decomposition products have been classified in three general groupings - pearlite, bainite, and martensite. Of the three decomposition products, bainite has received only scant attention. On occasions it was found that not all the austenite was transformed (4) especially in higher carbon steels containing high percentages of manganese, nickel, and chromium. This untransformed

or retained austenite has caused some investigation and several methods of quantitative analysis have been tried.

Some factors affecting the retention of austenite are as follows:

- (1) Carbon content
- (2) Quenching rate (quenching media)
- (3) Austenitizing Temperature
- (4) Sub-atmospheric cooling
- (5) Cold working
- (6) Tempering temperature and time

The fact that some austenite was retained on quenching higher carbon steels was known since the very early days of metallurgy.(5) It was originally felt that more austenite was retained when more drastic quenching from a higher temperature was employed. This idea was later discovered to be incorrect, when certain alloy steels retained more austenite after oil quenching than they did after water quenching (7). The suggested explanation for this phenomenon was based primarily on the effect of stresses and stress distribution during quenching. When the problem was considered from a stress standpoint, care had to be taken to distinguish between compressional and tensional stresses within the steel being considered. Since austenite has a greater density

than martensite, compressive stresses will promote the retention of austenite while tensional stresses will promote its decomposition. In connection with this idea, experimental evidence showed that more austenite was retained in the exterior, on water quenching, while upon oil quenching, more austenite was retained in core area.

The earlier work caused some disagreement on the lowest possible carbon content at which austenite was retained regardless of the rapidity of quenching rate. Wever and Engel (11), by the use of X-ray analysis found that a minimum of 0.60% carbon was necessary in quenched steels for the retention of austenite. Davenport and Bain (12), claimed that they found traces of retained austenite in 0.54% carbon steel that was quenched.

Esser and Cornelius (13) found that the maximum amount of retained austenite results at cooling rates just below that of the critical cooling velocity. With either increasingly higher or increasingly lower cooling rates, the amount of retained austenite was found to steadily decrease. The idea of cooling rates was extended as the possible reason why more retained austenite was found in small sections quenched in oil than in corresponding sections quenched in water. The cooling rate of the oil was more nearly that of the critical

cooling velocity and thus retained more austenite.

The maximum amount of austenite was retained when the steel was quenched from just above the Ac_3 or Ac_m line. High-temperature quenching was found to give less retained austenite (5).

Several ideas have been put forward on the retained austenite to martensite transformation that occurred during cooling to very low temperatures. Early experimenters (14) found that the transformation occurred by a step-wise cooling to sub-atmospheric temperatures, transformation began at the -20°C . step. On holding at this temperature the transformation ceased after a period of time and no further transformation occurred until the temperature was again dropped. Complete, or nearly complete transformation occurred if enough increments of temperature drop were applied. From the step-wise action of the transformation it was believed that the real cause of the austenite to martensite change was brought about by the deformations, stresses, and strains which had occurred during cooling. Fletcher and Cohen (6), stated that aging at room temperature between the hardening and sub-cooling treatments lowered the temperature at which the retained austenite started to transform on sub-cooling and reduced the amount of transformation

achieved by any given cooling treatment. Virtually complete decomposition of the retained austenite could be accomplished by sub-cooling to -250°F. to -260°F. , if the prior time at room temperature was kept within several minutes. Transformation of retained austenite due to relief of stresses and strains was definitely established when the effect of cold working on the retention of austenite was studied.

Hardened steels which contained 0.55% carbon were found by Bain (7) to be susceptible to retained austenite after quenching. Those alloy steels in which more than the normal quantities of nickel, manganese, and chromium were present can have a carbon content even lower than 0.55% and still retain unstable austenite. Tamaru and Sekito (15), found by X-ray studies evidence of retained austenite in steel containing as little as 0.40% carbon. Retained austenite was transformed by heating to a suitable temperature for a definite length of time. Partial transformation has occurred at very low temperatures, with the occasional formation of cracks.

A proportion of retained austenite amounting to 10% to 25% has been found in commercial steels. In many steels, the presence of a surprisingly large proportion of austenite had scarcely any effect on the hardness of the quenched steel. To obtain a reduction

of 10 points Rockwell required the retention of fairly large amounts of austenite. The explanation for this was based on the uniform distribution and orientation of the austenite in the martensitic structure. Bain (7) states that some high chromium steels quenched from an austenitizing temperature have been found to contain as high as 80% to 90% retained austenite.

The austenite in plain carbon steels has been substantially unchanged during heating for brief periods at 450°F. The complete transformation of austenite has been verified by X-ray diffraction and dimension change with tempering.

Careful studies (7) made on the isothermal transformation of retained austenite reveal that the product of transformation at the tempering temperature was not hard martensite, but rather one of the slightly softer structures of the bainite group. The hardness of this bainite was just a little greater than that of the tempered martensite.

The behavior of some steels to get slightly harder at room temperature as a large quantity of time has passed indicates that possibly the retained austenite, which is unstable after quenching, has slowly transformed into martensite. Bain (7), has referred to this phenomenon as a lingering austenite transformation. Tempering

at low temperatures, such as 200°F., has greatly speeded the transformation or "aging period" of freshly quenched high carbon steel.

French (8) stated that in a steel of around eutectoid carbon, it was found that the water quenched steel with less than 3% austenite had poor fatigue resistance, while the same steel quenched in oil contained 5% retained austenite and showed an appreciable improvement in the fatigue limit. The effect of the 5% austenite was thought to exert a cushioning action rather uniformly throughout the cross-section of the fatigue sample and thus cause increased fatigue resistance.

When wear resistance is desired, the retention of large quantities of austenite is found to be a disadvantage, since it is much softer and more plastic than martensite.

French(8) also stated that if sufficient quantities of manganese and nickel were added to a steel, it could remain completely austenitic.

Hardened steel, containing tetragonal martensite and retained austenite, passes through three structural changes on tempering (9). During the first stage (200°F. to 350°F.) the tetragonal martensite undergoes a decomposition which causes a precipitation in the higher

carbon concentration regions and this transition precipitation accounts for the darkening of the martensite plates. During the second stage of tempering (450°F. to 550°F.) it is quite certain that the retained austenite is transformed. The transformation product has the general appearance of an acicular bainite. The main reason for believing that the transformation product is bainite is that the second stage tempering temperatures are well above the martensitic range of transformation. The third stage of tempering (550°F. to 750°F.) is characterized by the decomposition of the transition precipitate formed during the first two stages. The decomposition forms cementite particles which gradually coalesce into a spheroidized structure with a ferrite matrix.

Liedholm (10), supports Bain's statement on the transformation of retained austenite in plain carbon steels at a range of temperatures in the vicinity of 455°F. The transformation reaction causes an increase in magnetization of carbon steel by about 3%. It was found also that the relationship between the amount of austenite present and the magnetic properties defied the attempt of mathematical formulation. The investigation on cobalt high speed steels indicated that considerable austenite was retained after tempering at temperatures

of 900°F. or less. The retained austenite did, however, decompose rapidly upon tempering at 1000°F. and higher temperatures. The first changes in the austenite occurred at temperatures between 700°F. and 800°F. which indicated that the austenite transformation occurred over a range of temperatures rather than a sharp change at a definite temperature. No evidence was found in the literature to support the transformation of retained austenite in plain carbon steels over a range of temperatures. In view of the fact that the transformation of retained austenite in alloy steels occurred over a wide range it may be assumed that a similar system of transformation occurred in the plain carbon steels.

Experimental Procedure

Part I

Relation of Carbon Content to the Amount of Retained Austenite

Five steels were chosen for the experimental work, one plain carbon steel SAE 1010 and four alloy steels SAE 2015, SAE 2340, SAE 3145, and SAE 4640. The analysis of the five steels were given in table I.

Table I

	<u>C</u>	<u>Mn</u>	<u>P</u>	<u>S</u>	<u>Cr</u>	<u>Ni</u>	<u>Mo</u>
SAE 1010	.15	.55	.016	.045			
SAE 2015	.33	.54	.017	.024	.33	.73	
SAE 2340	.297	.71	.011	.017	.22	3.42	
SAE 3145	.40	.72	.016	.020	.69	.139	
SAE 4640 (Aver.Spec)	.40	.65				1.82	.25

The bars were first cut to a convenient length (6 inches) and then placed in a lathe chuck to be faced down on both ends and center-drilled. Upon center-drilling each end of the five bars, they then were turned on centers to the largest possible diameter giving a taper of no more than .001 of an inch from one end to the other. After all the preliminary machining was completed, the bars were then ready to be case carburized.

The carburizing was done in a 2.0" steel pipe carburizing bomb, using a commercial solid carburizing mixture of the following analysis:

Table 2

BaCO ₃	10-12%
Na ₂ CO ₃	2-3%
CaCO ₃	2-3%
Coke	25-30%

Charcoal (Type F.S.R) Balance

Two of the smaller diameter bars were placed in a bomb together, while the larger bars were carburized individually. When two bars were placed in the same bomb together care was exercised to keep the bars equidistant from the walls of the bomb and from one another. The commercial carburizer was packed very tightly about the samples. The sealed bombs were placed in a muffle type furnace controlled at 1700°F., and left there for a period of 13 hours. At the end of the 13 hours, the bombs were removed and allowed to cool in still air.

The carburized bars were then placed on lathe centers again and checked first for possible warping by the use of a dial indicator. If it was found that the bar had warped appreciably it was aligned by a few well placed hammer blows, while on the lathe centers. Maximum warping occurred, as would be assumed, in the smaller diameter bars. The large bars (SAE 3145 and SAE 4640) exhibited practically no deformation during carburizing. After the proper alignment had been secured

the bars were ready to be machined. The machining operation consisted of removing, by the use of a lathe, layers of the carburized case of very definite thickness and catching the chips from each individual layer in a clean, oil free, envelope. The envelope was carefully marked to designate the steel and the exact layer it contained. The layers were removed in a systematic way, the first layer was .002 of an inch thick (a diameter decrease of .004) and each following layer was .005 of an inch thick, to a depth of approximately .062 inches or the core whichever came first. It was possible to tell when the core had been reached by the ease of machining and the type chip produced. The entire length of the test bar was not machined, thus leaving a stud about .75 inches long to be used later in the metallographic analysis of the carburized cross-section of the respective bar.

The steel chips were then analyzed for their carbon content in a standard carbon train (see diagram). The carbon contents of the various layers of the five steels were determined and plotted against the distance from the surface of the respective bars. The graph of carbon content vs. the distance from the edge of the bar indicated the carbon gradient in the case. Care was

exercised to repeat exactly each step of the procedure involved in the carbon analysis so that reproducible results were obtained. Bureau of Standards samples were used to check the accuracy of the "carbon train" at the beginning of each run.

The .75 inch studs which were not machined were then heated in used carburizing compound to a temperature of 1700°F throughout and quenched. The quenching media was stirred water for the SAE 1010 and stirred oil (100 deg. cent.) for the four alloy steels. The five samples were then tempered at 400°F. for a period of 1.5 hours. The tempering was done to transform the light etching tetragonal martensite to a body centered cubic martensite which was dark etching when 3% nital was used as an etchant, thus making a sharp differentiation between it and the light etching retained austenite. All samples were then mounted in bakelite with a steel band mounted around their periphery to help maintain a flat edge on the polished samples. Polishing was done in two steps; first the sample was lapped on a lead lap using medium lapping compound, then it was finished on a felt wheel using levigated alumina as the polishing compound. The polished samples were then etched with 3% nital.

After etching the samples were ready to be photomicrographed. The procedure used in taking the photomicrographs was to start at the edge of each sample

and proceed to the core taking photographs at 500 magnifications of each .0064 of an inch until the retained austenite was no longer visible. This procedure gave slight overlapping in each photomicrograph, allowing later matching of prints and thus forming a continuous photomicrograph from case to core.

Part II

Effect of Quenching Rates on Retained Austenite

The same five steels were used for the second phase of the experiment as were used in Part I. The bars were turned on a lathe to 0.500 inches diameter by 4.00 inches long. Flats were milled on each side of the bars (180 degrees apart) to a depth of .010 of an inch. One end of each bar was faced off while the other end was drilled and tapped to accomodate the 10-32 thread on the standard Jominy test bar holder. A sixth bar was machined from SAE 4640 steel to a diameter of 1.000 inch and a length of 4.000 inches and milled and tapped similarly to the other five bars. The six bars were then case carburized for a period of 13 hours at 1700°F. The carburizing procedure was the same as that used in Part I. All six bars were then cleaned carefully and copper plated in a cyanide bath for 0.50 hours at a current density of 15 amperes per square foot.

The six plated bars were then placed in a furnace

containing burning used carburizer which produced a slightly reducing rather than oxidizing atmosphere. The bars were heated completely to a temperature of 1700°F. All the bars were then quenched according to the standard Jominy end-quenching procedure (see detailed diagram), the 0.50 inch bars being quenched in a 0.25 inch stream of water while the 1.00 inch bar was quenched in a 0.50 inch stream of water.

The quenched bars were then polished on the flats etched (3% nital) and examined microscopically to determine the critical transition points on the bars. Representative photomicrographs were then taken at 500 magnifications at these points.

Rockwell-C hardness readings were then taken on the polished copper-free flats of the six end-quenched bars. The readings were taken every sixteenth of an inch for 1.50 inches from the quenched end, and then every eighth of an inch between 1.50 inches and 2.50 inches from the quenched end. These Rockwell-C values were then plotted as hardness (ordinate) vs. distance from the quenched end of the bar (abscissa). A 1.00 inch bar as well as a 0.50 inch bar of SAE 4640 steel was end-quenched in hopes of obtaining some correlation of the cooling rates in the 0.500 inch bar as compared to the known cooling rates in the 1.00 inch bar.

Part III

Transformation Range of

Retained Austenite in SAE 1010 (carburized)

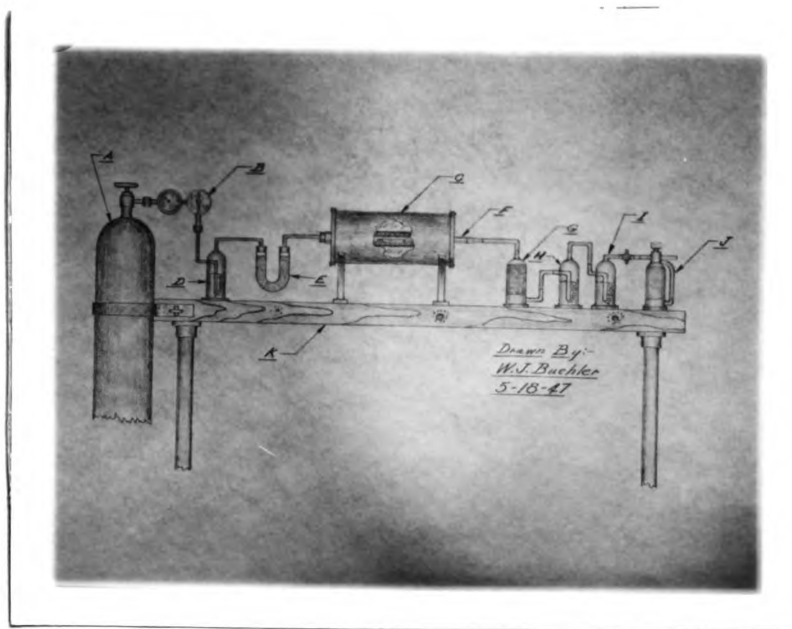
Five samples of SAE 1010 (carburized, 1700°F., 13 hours, solid commercial carburizer) were quenched in stirred water. Each of the five samples were then tempered carefully at a different temperature, temperatures being 350, 400, 425, 440, 450°F. and the time of tempering 1.5 hours. The samples were then mounted as in part I, in bakelite. Polishing was done on a lead lap and a felt wheel. The polished samples were etched with 3% nital by swabbing the polished surface with saturated cotton swabs.

The same approximate distance was chosen from the edge on each sample and a photomicrograph was taken at 500 magnifications. Effort was made to choose a representative spot characteristic of the amount of retained austenite in the chosen distance from the edge.

One photomicrograph was taken of SAE 2015 (carburized, 1700°F, 13 hours, solid commercial carburizer) quenched in oil (100 deg. cent.) and tempered at 430°F. This was done to note any transformation in retained austenite over that of the 400° tempered sample.

Figure 1

The apparatus used for the carbon determinations

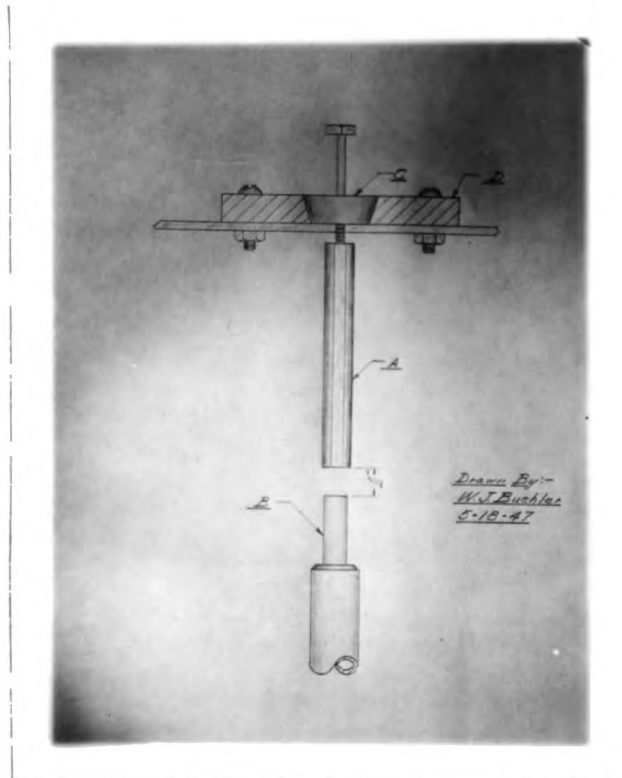


Key

- A- Oxygen supply tank
- B- Gas pressure regulator
- C- Combustion furnace
- D- Oxygen washing bottle (conc. H_2SO_4)
- E- Ascarite tube (CO_2 removal)
- F- Combustion tube
- G- Zinc pellets
- H- CO_2 and O_2 washing bottle (conc. H_2SO_4 and CrO_3)
- I- CO_2 and O_2 washing bottle (conc. H_2SO_4)
- J- Ascarite weighing bottle
- K- Bench

Figure 2

The apparatus used for the end quenching



Key

- A- Carburized test bar ($\frac{1}{2}$ " dia. x 4")
- B- Water supply nozzle (stream $\frac{1}{4}$ " dia., $2\frac{1}{2}$ " head)
- C- Test bar adapter and centering attachment
- D- Test bar holder

Experimental Results

The experimental results were divided into three major divisions and several sub-divisions, as follows:

Part I

- (a) Carbon gradient data for carburized SAE 1010, 2015, 2340, 3145, and 4640.
- (b) Graphs of the carbon gradient data for the five steels listed in Part I (a).
- (c) Photomicrographs of retained austenite in cases of the five steels listed in Part I (a).

Part II

- (a) End-quenched hardness data from the five 0.5 inch and one 1.0 inch, end-quenched bars.
- (b) Graphs of the end-quenched data of Part II (a).
- (c) Microstructure of end-quenched bars (observing the polished flats).
- (d) Photomicrographs of the critical points on the polished flats of the five 0.5 inch end-quenched bars.

Part III

- (a) Photomicrographs showing the transformation of retained austenite in SAE 1010 and SAE 2015 with increased tempering temperatures.

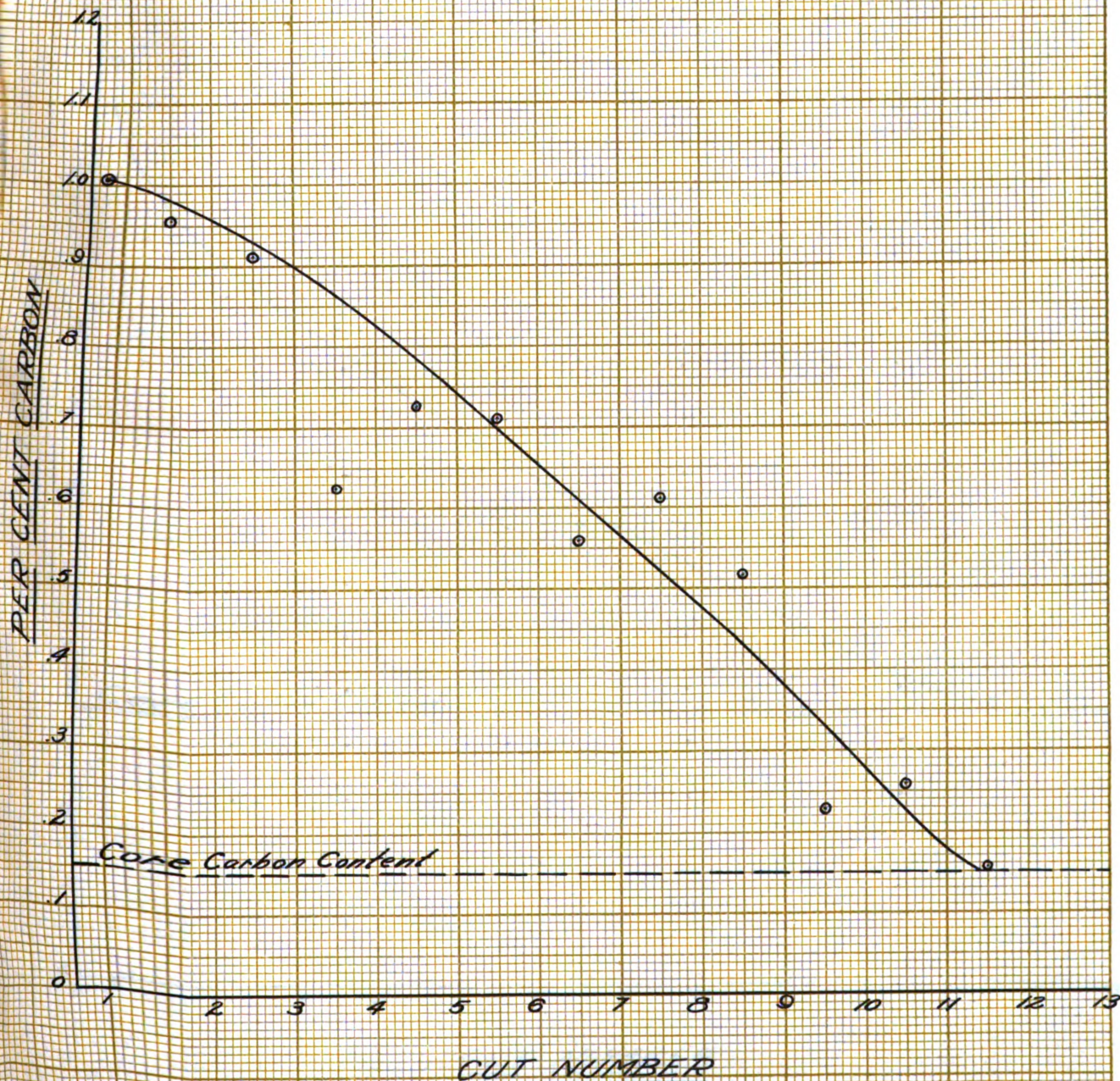
Table 7

Data Of Carbon Gradient In Carburized

SAE 4640 Steel

<u>Cut No.</u>	<u>Distance From Surface</u>	<u>Sample Wt.</u>	<u>Wt. CO₂</u>	<u>% Carbon</u>
1	.000 - .002"	1.000 gr	.0381 gr	1.040
2	.002 - .007"	1.000 gr	.0407 gr	1.110
3	.007 - .012"	1.000 gr	.0355 gr	.968
4	.012 - .017"	1.000 gr	.0322 gr	.878
5	.017 - .022"	1.000 gr	.0307 gr	.837
6	.022 - .027"	1.000 gr	.0303 gr	.826
7	.027 - .032"	1.000 gr	.0275 gr	.750
8	.032 - .037"	1.000 gr	.0242 gr	.660
9	.037 - .042"	1.000 gr	.0242 gr	.714
10	.042 - .047"	1.000 gr	.0242 gr	.660
11	.047 - .052"	1.000 gr	.0207 gr	.565
12	.052 - .057"	1.000 gr	.0162 gr	.440

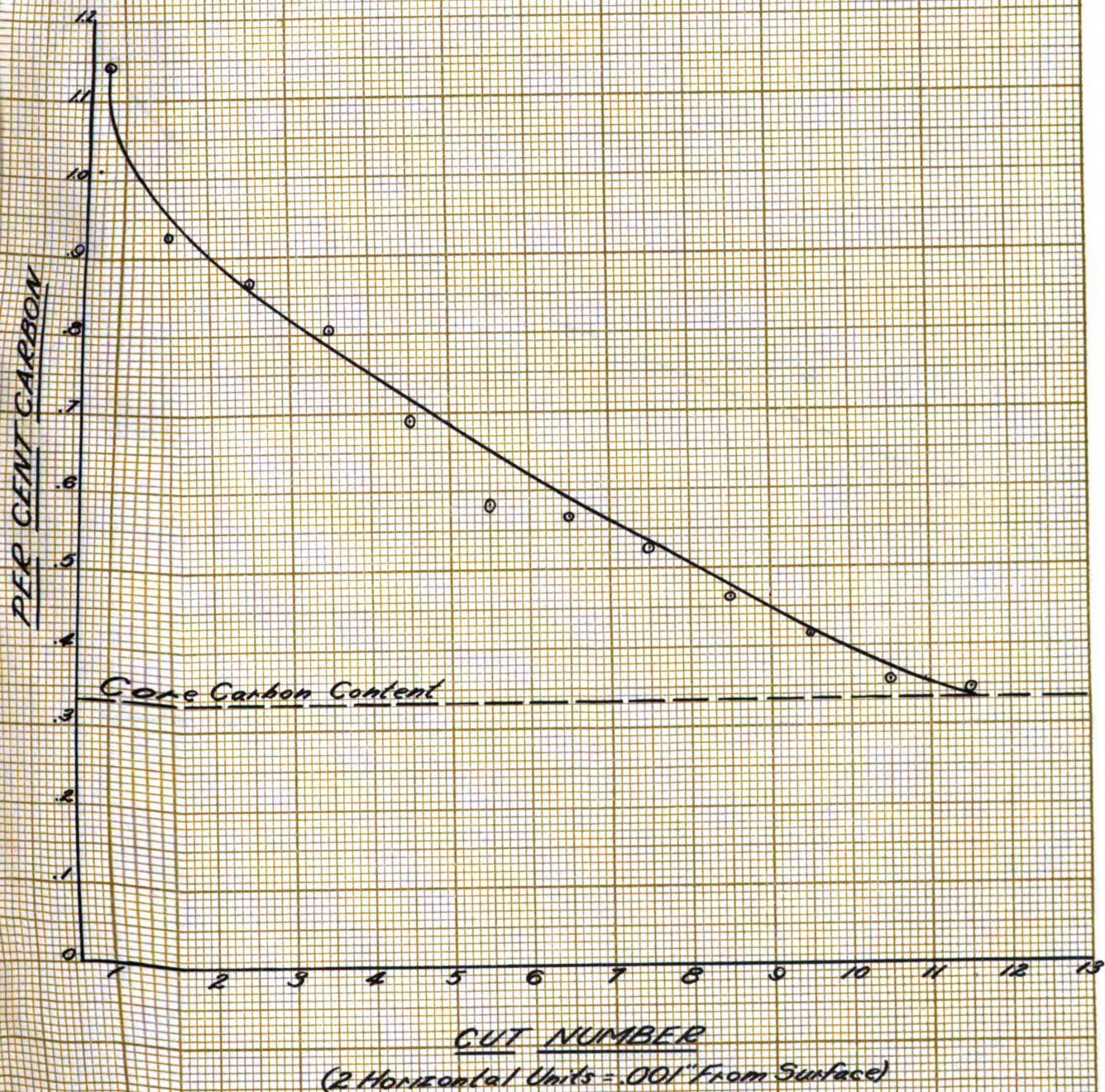
FIGURE 3
GRAPH OF CARBON GRADIENT
IN CARBURIZED SAE 1010 STEEL



CUT NUMBER
 (2 Horizontal Units = .001" From Surface)

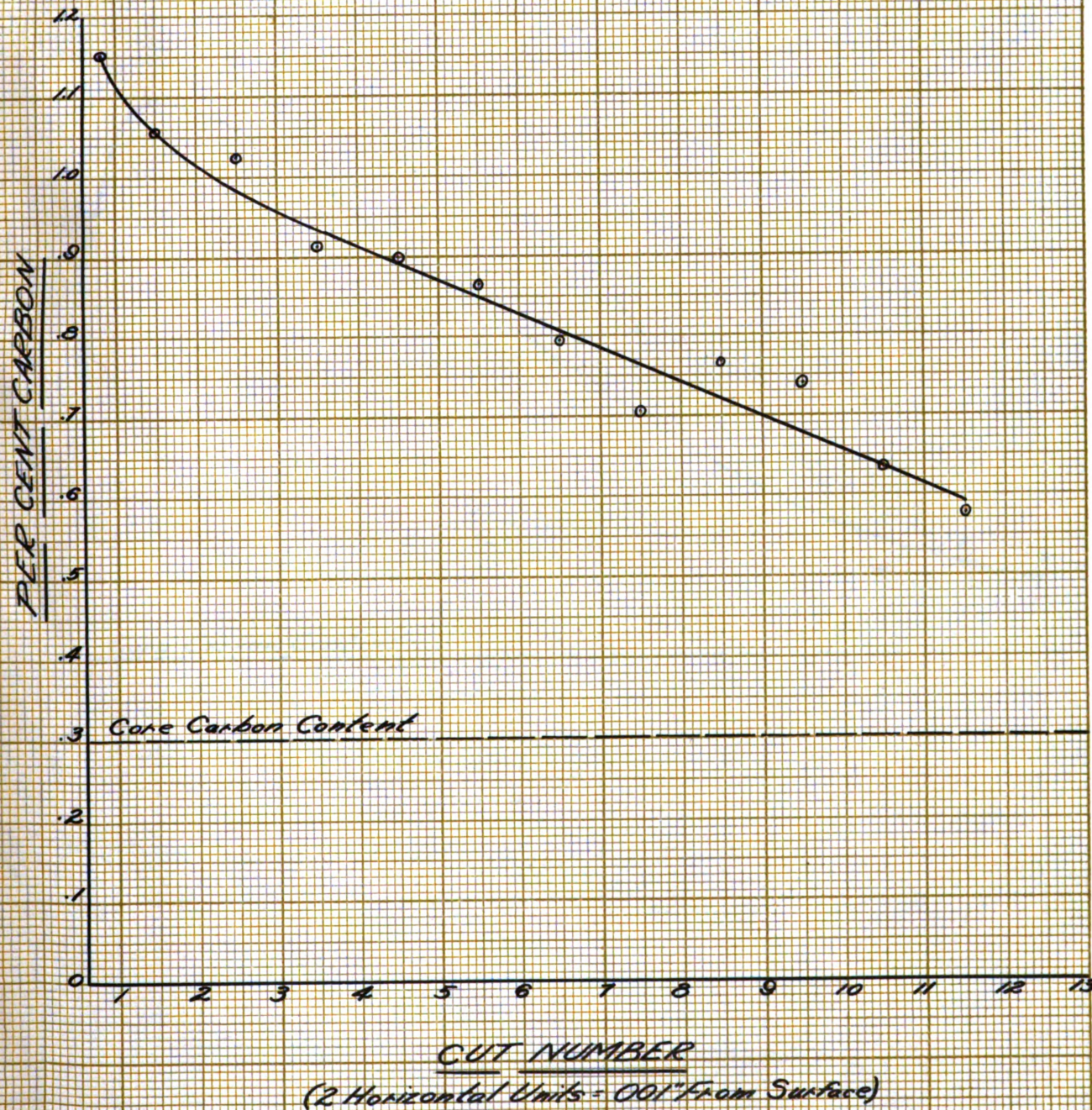
May 15, 1947

FIGURE 4
GRAPH OF CARBON GRADIENT
IN CARBURIZED SAE 2015 STEEL



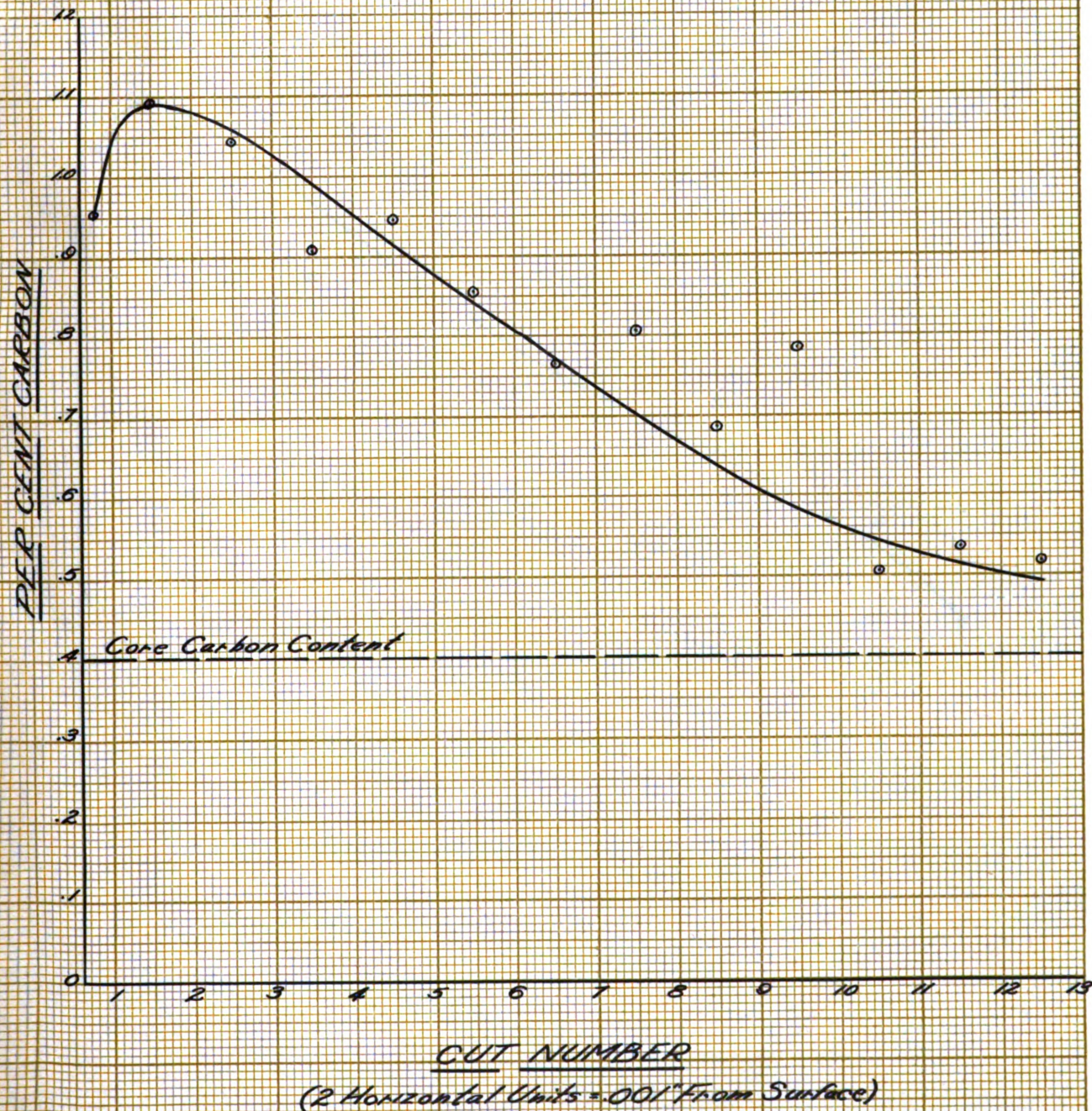
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FIGURE 5
GRAPH OF CARBON GRADIENT
IN CARBURIZED SAE 2340 STEEL



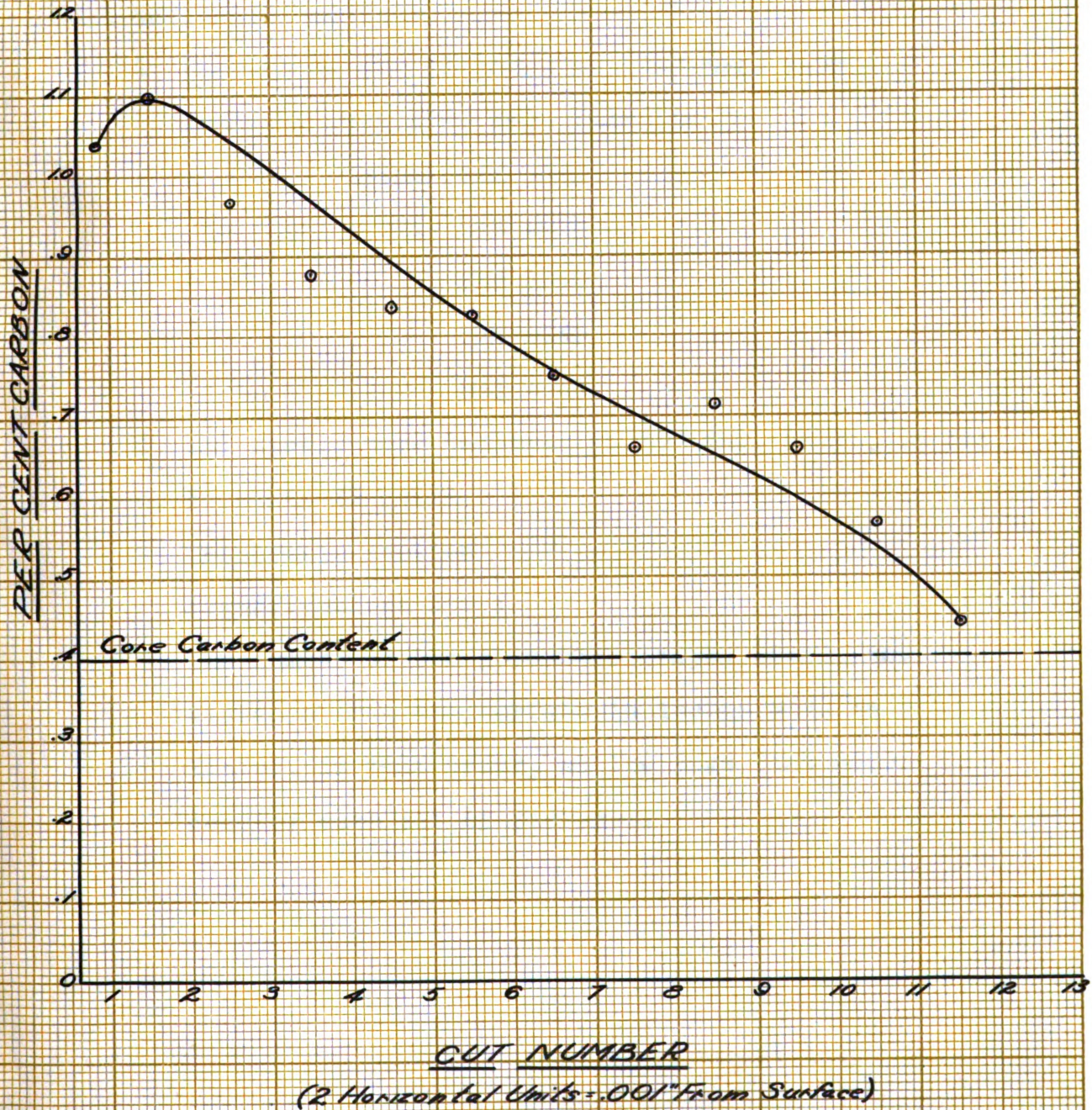
May 15, 1947

FIGURE 6
GRAPH OF CARBON GRADIENT
IN CARBURIZED SAE 3145 STEEL



May 15, 1947

FIGURE 1
GRAPH OF CARBON GRADIENT
IN CARBURIZED SAE 4640 STEEL



May 15, 1947

Part I Photomicrographs

The photomicrographs in this section represent steels that were all subjected to the following treatment and specifications.

1. Carburized for 13 hours at 1700 deg. Fahr.

2. Quenched from 1700 deg. Fahr. in

Water- SAE 1010

Oil- SAE 2015

SAE 2340

SAE 3145

SAE 4640

3. All steels were tempered at 400 deg. Fahr., 1.5 hrs.

4. Etchant- 3% nital

5. Transverse section

6. Magnifications 500 X

7. The number of the photomicrograph, steel, and distance from the surface in inches will be listed, in that order, on the page just proceeding each set of pictures.

1

0101 848

8000.0-0000.0

2

0101 848

8000.0-0000.0



3

SAE 1010

0.0128-0.0192

4

SAE 1010

0.0192-0.0256

3

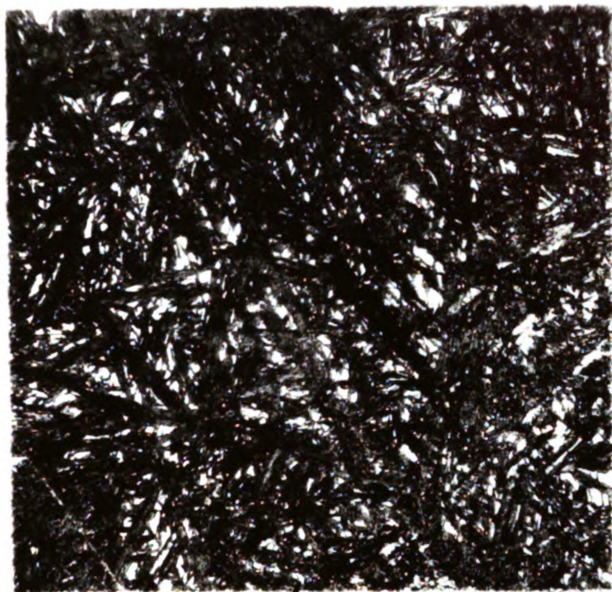
0701 112

RS10.0-1110.0

4

0101 111

RS10.0-RS10.0



5

SAE 1010

0.0256-0.0320

6

SAE 1010

0.0320-0.0384

3

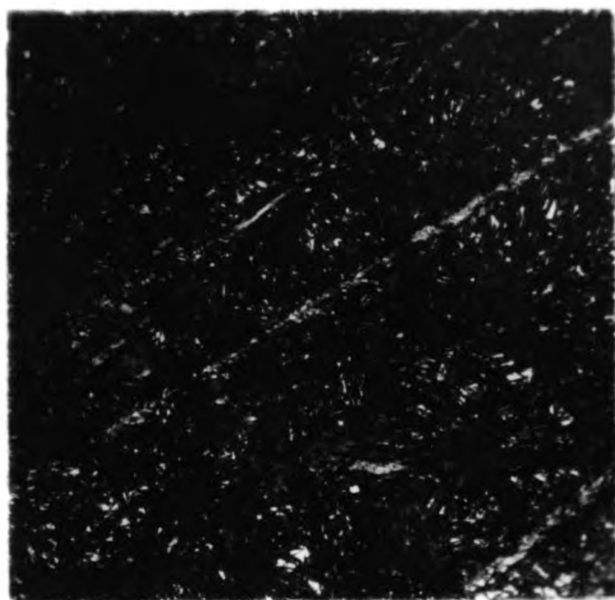
0101 417

01.0.0-334.0

6

0101 417

4133.0-0133.0



7

SAE 1010

0.0384-0.0448

8

SAE 2015

0.0000-0.0064

7

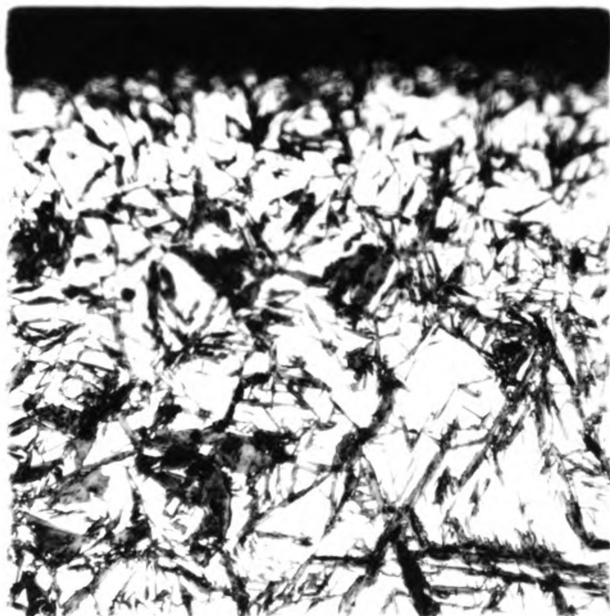
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0101-010

0000.0-0000.0



9

SAE 2015

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10

SAE 2015

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9

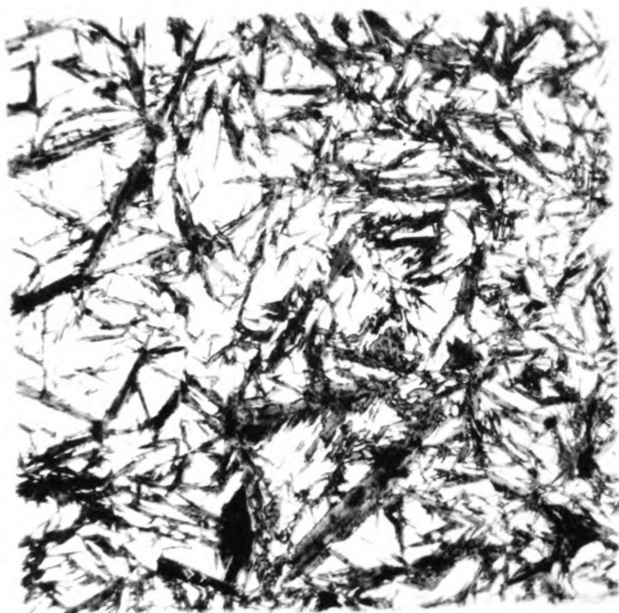
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SLIP 111

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SAE 2015

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12

SAE 2015

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11

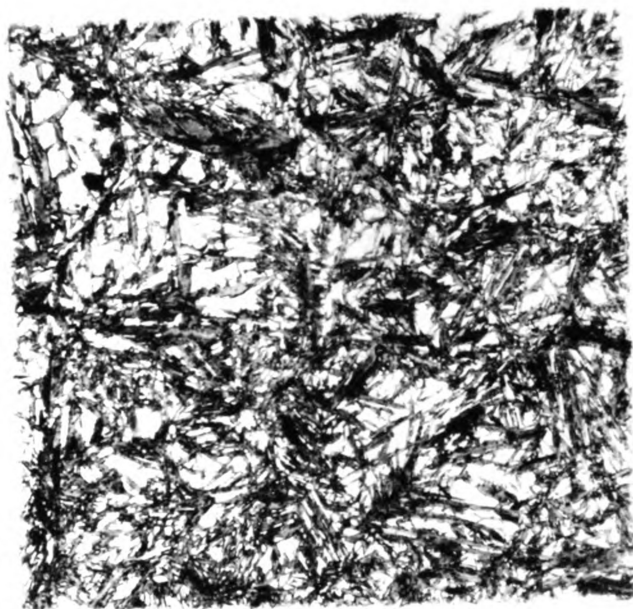
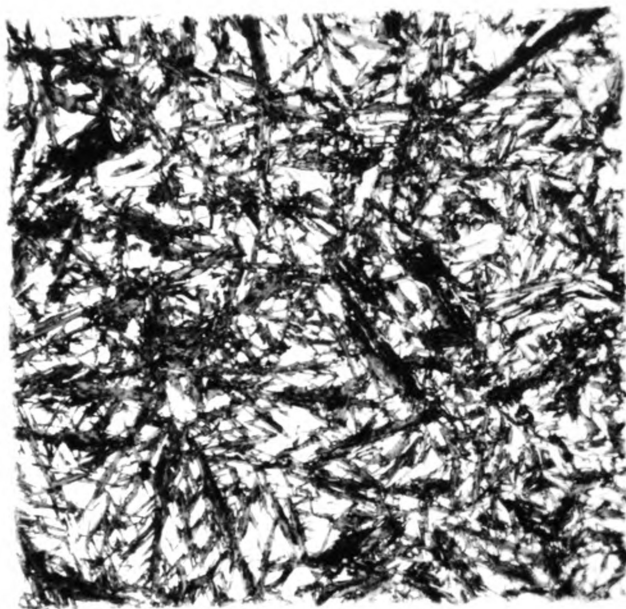
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PL 86-360

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14

SAE 2015

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11

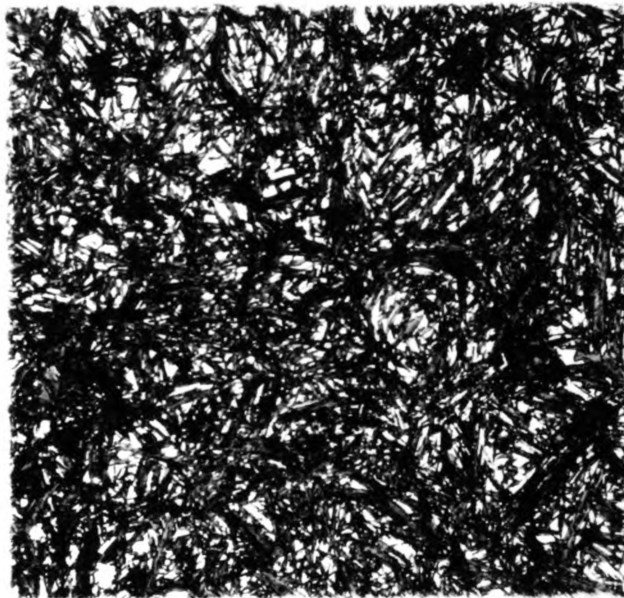
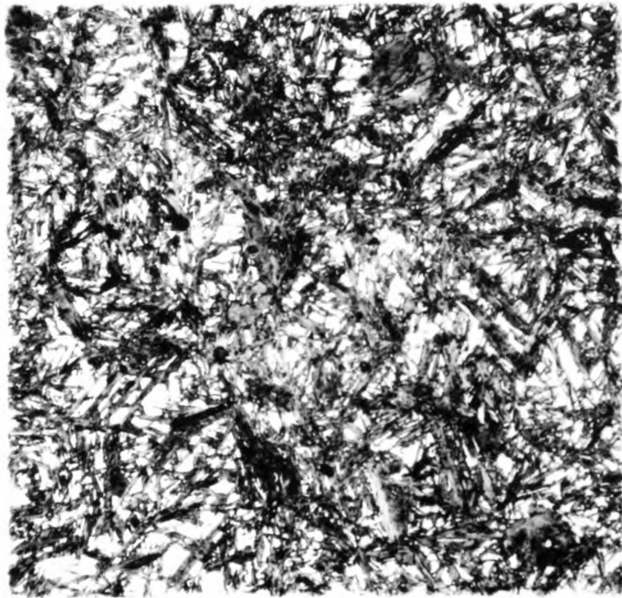
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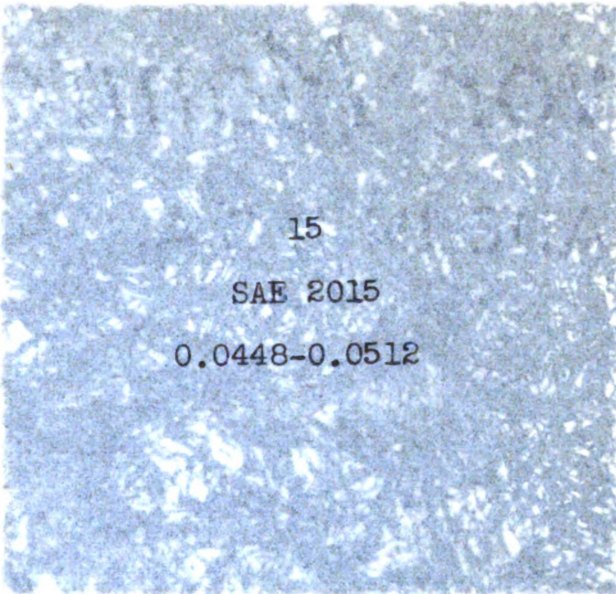
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1111 1111

1111 1111 1111 1111

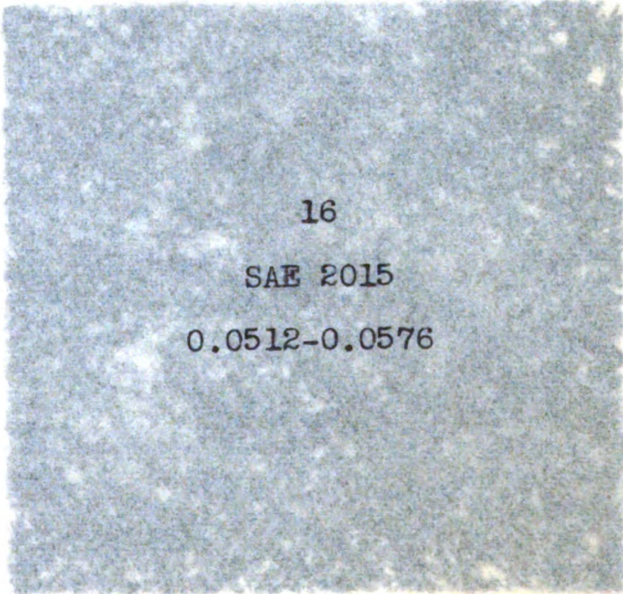




15

SAE 2015

0.0448-0.0512



16

SAE 2015

0.0512-0.0576

18

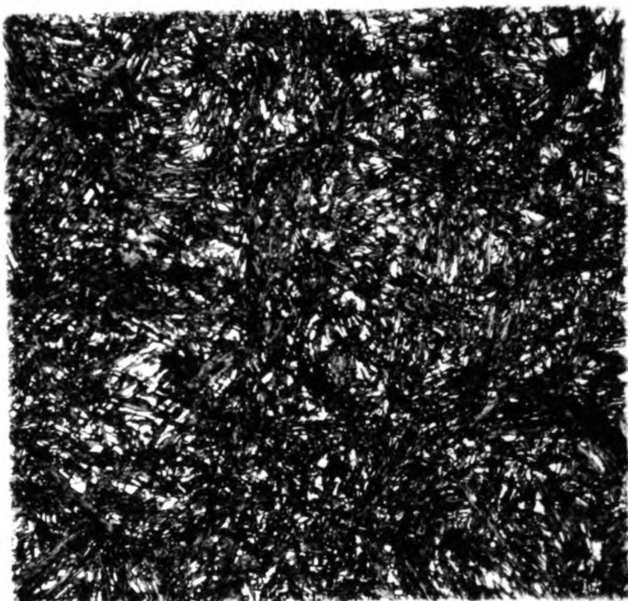
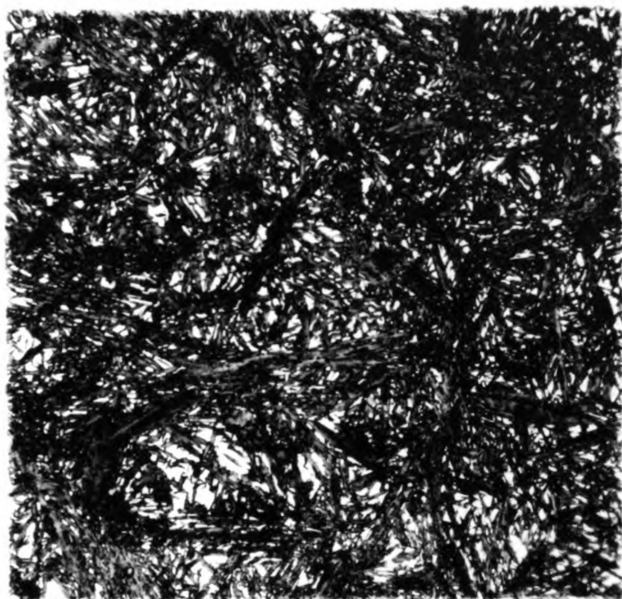
2015-2016

0.0000-0.0000

18

2015-2016

0.0000-0.0000



17

SAE 2015

0.0576-0.0640

18

SAE 2015

0.0640-0.0704

VI

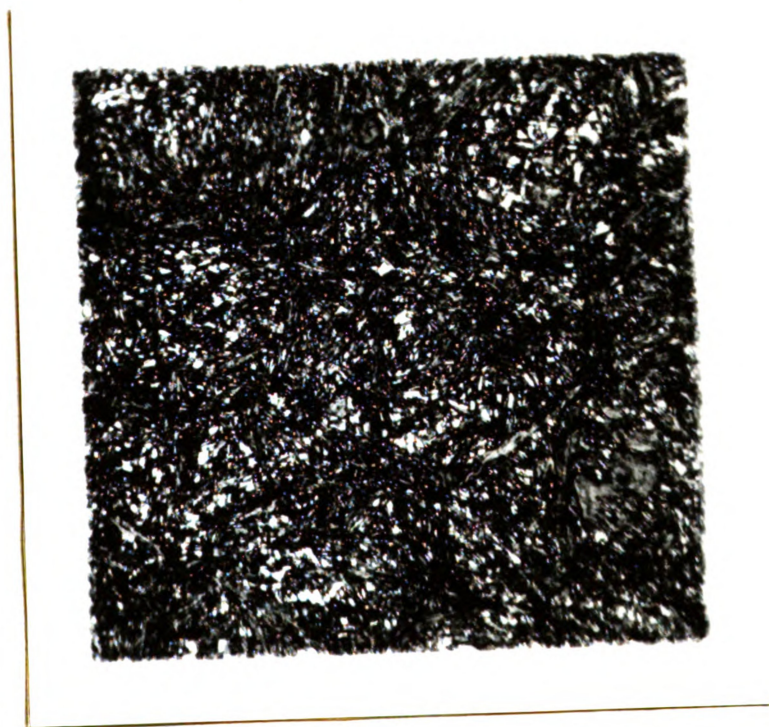
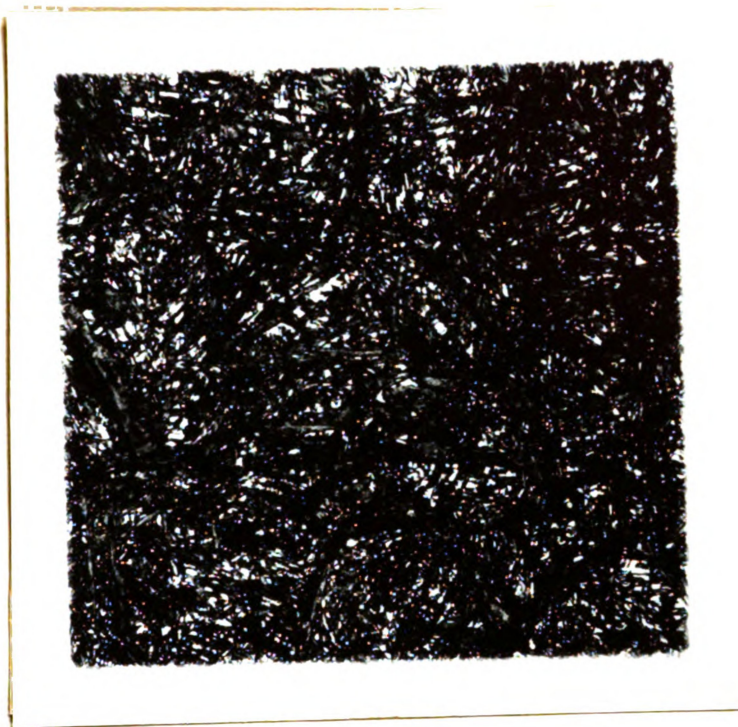
CHURCH

0.000.0-1.000.0

VI

CHURCH

0.000.0-0.000.0



19

SAE 2340

0.0000-0.0064

20

SAE 2340

0.0064-0.0128

61

0000 000

0000.0-0000.0

61

0000 000

0000.0-0000.0



21

SAE 2340

0.0128-0.0192

22

SAE 2340

0.0192-0.0256

12

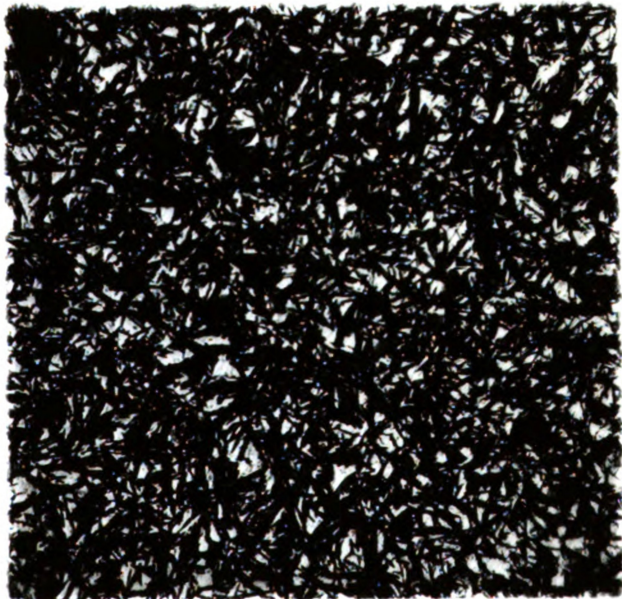
0001.0-0

0010.0-0010.0

12

0001.0-0

0010.0-0010.0



23

SAE 2340

0.0256-0.0320

24

SAE 2340

0.0320-0.0384

14

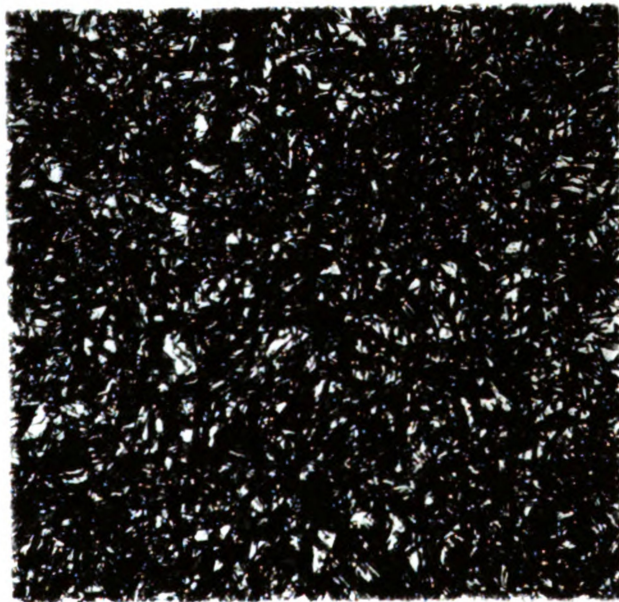
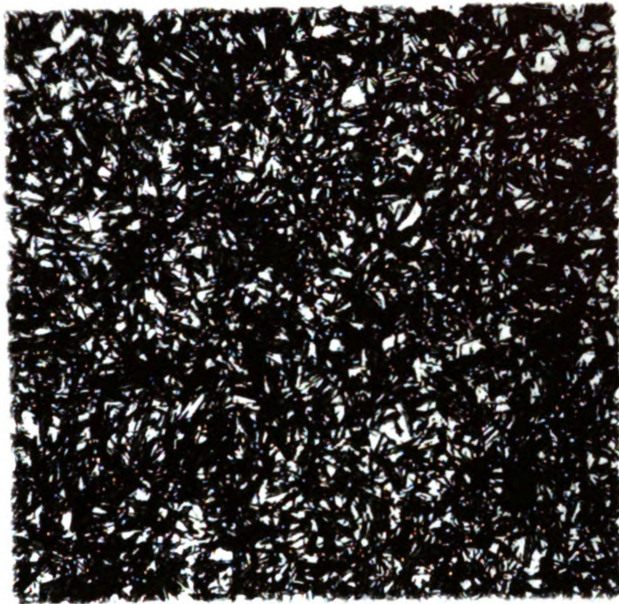
CH-1 5A2

0430.0-0430.0

14

CH-1 5A2

0430.0-0430.0



25

SAE 2340

0.0384-0.0448

26

SAE 2340

0.0448-0.0512

81

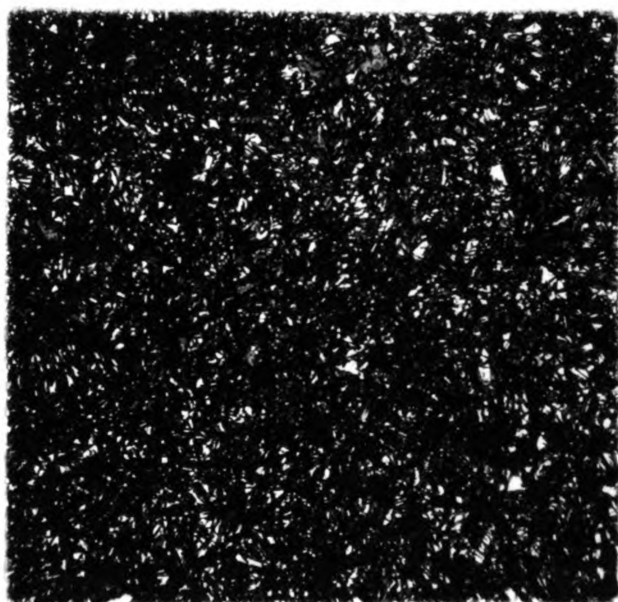
0-000-0000

0-000-0000

81

0-000-0000

0-000-0000



27

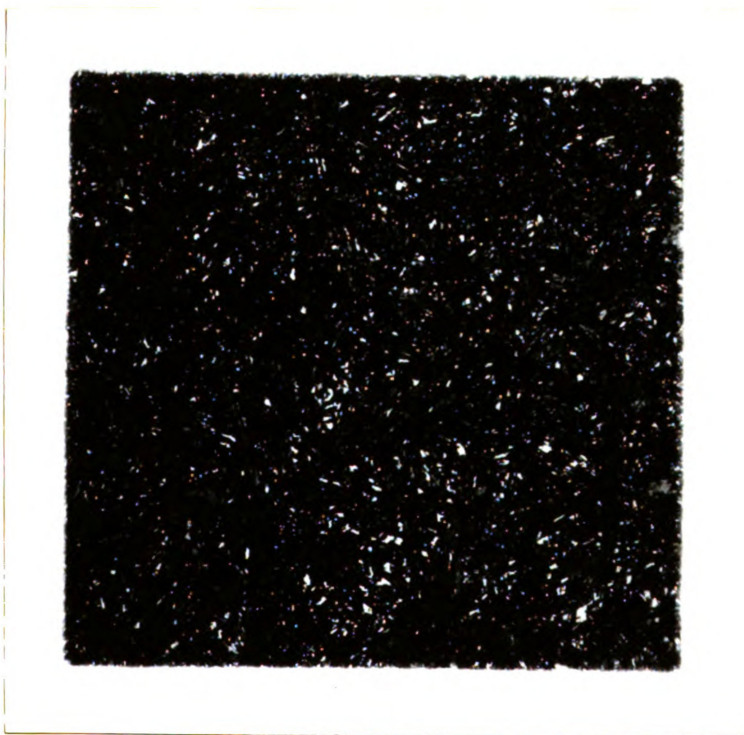
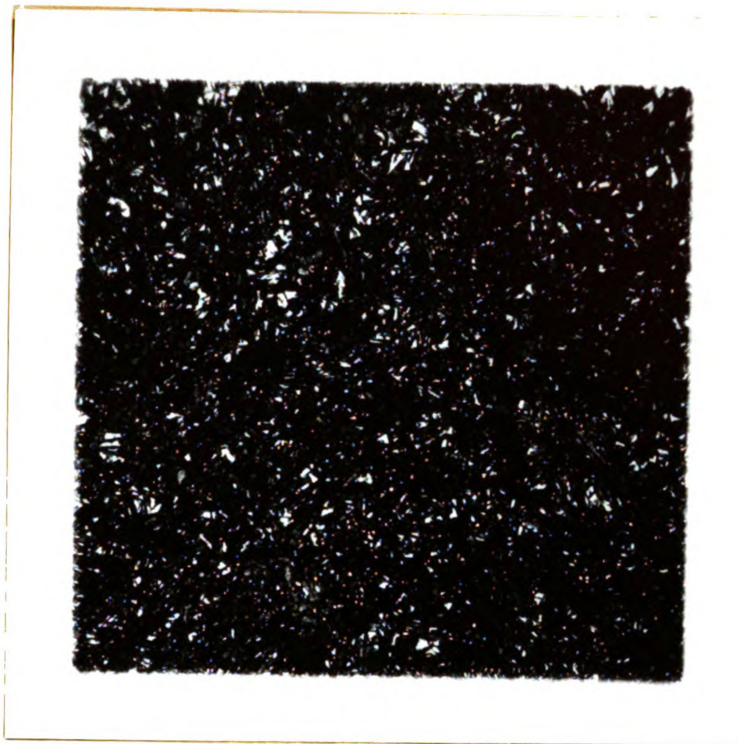
SAE 2340

0.0512-0.0576

28

SAE 2340

0.0576-0.0640



29

SAE 2340

0.0640-0.0704

30

SAE 3145

0.0000-0.0064

01

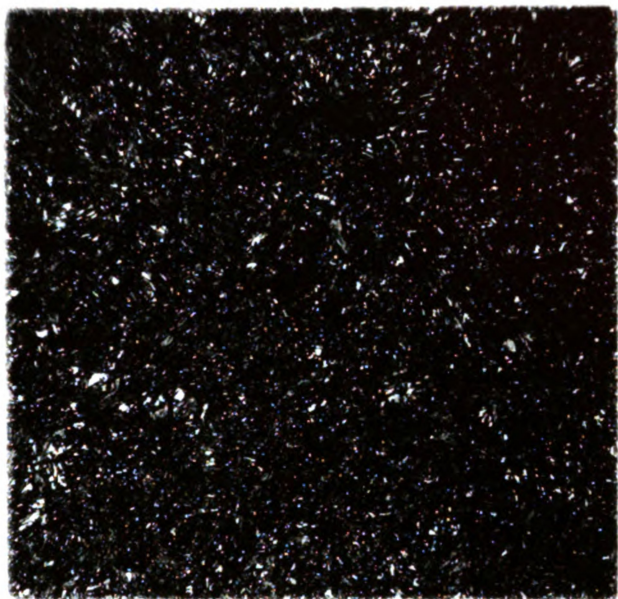
00-03 1A2

A.70.0-0000.0

03

00-13 1A2

A.70.0-0000.0



31

SAE 3145

0.0064-0.0128

32

SAE 3145

0.0128-0.0192

16

CP10: 5A7

5810.0-5810.0

16

CP10: 5A7

5810.0-5810.0



33

SAE 3145

0.0192-0.0256

34

SAE 3145

0.0256-0.0320

63

0013-111

0.0131-0.0131

64

0013-111

0.0131-0.0131

37

SAE 3145

0.0448-0.0512

38

SAE 3145

0.0512-0.0576

1

35

SAE 3145

0.0320-0.0384

36

SAE 3145

0.0384-0.0448

82

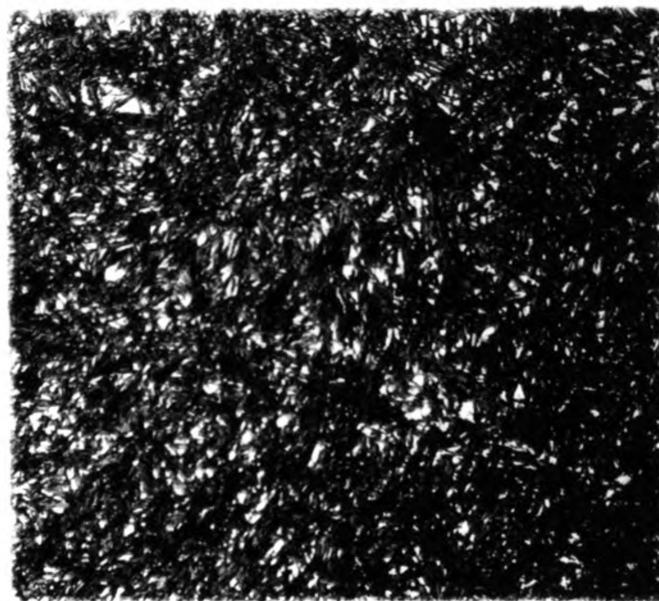
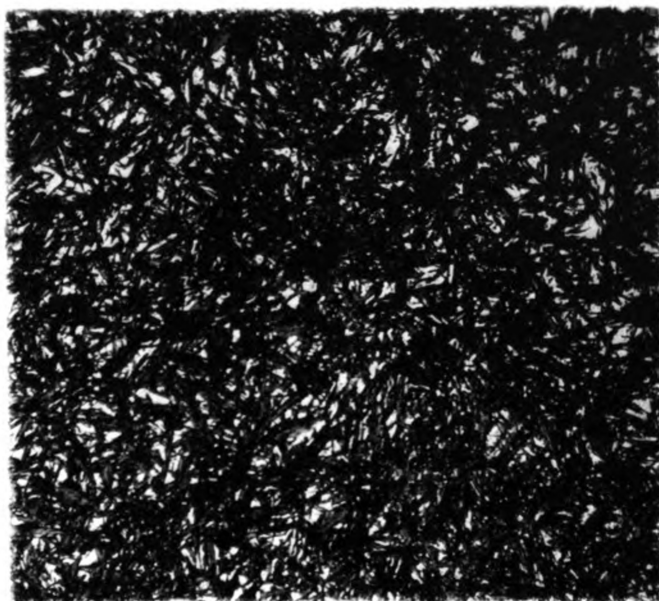
8415 1A2

8840.0-8860.0

83

8415 1A2

8840.0-8860.0



37

SAE 3145

0.0448-0.0512

38

SAE 3145

0.0512-0.0576

7.

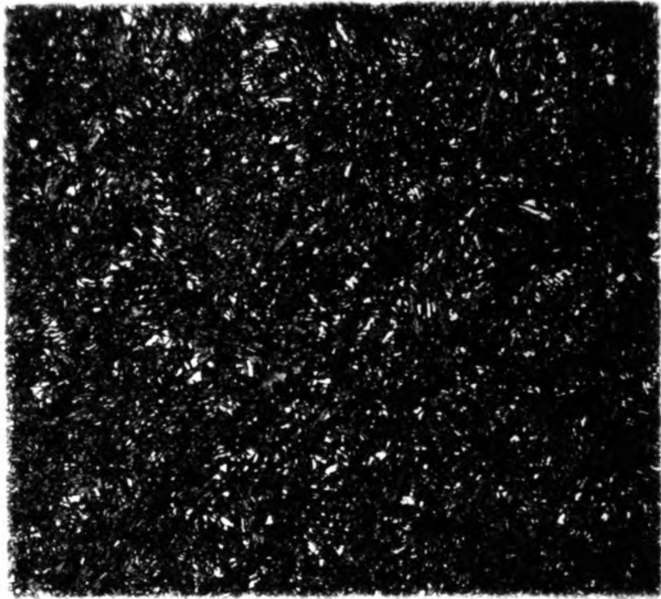
CAIR 342

8187.0-8040.0

88

CAIR 342

8780.0-8180.0



39

SAE 4640

0.0000-0.0064

40

SAE 4640

0.0064-0.0128

83

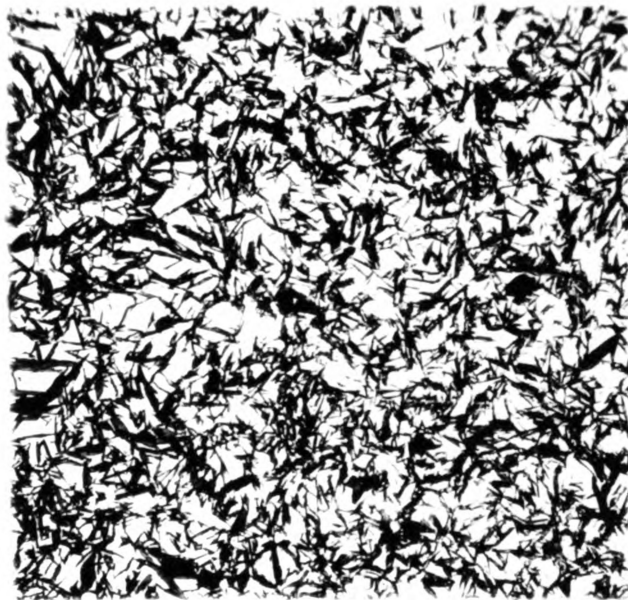
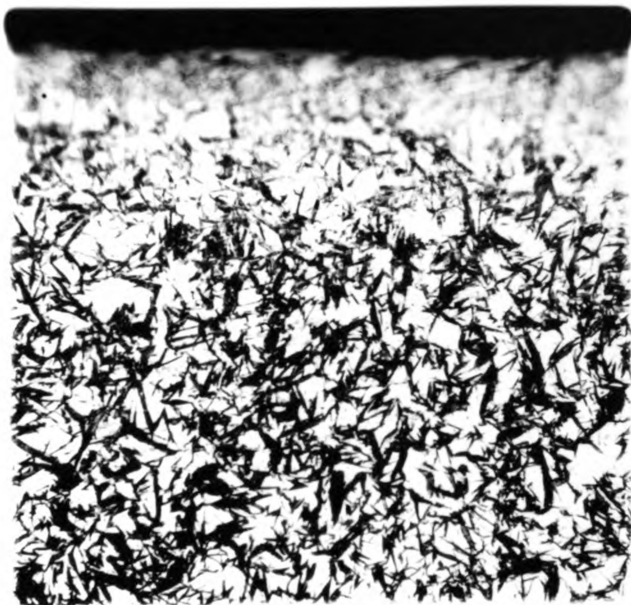
CPA-1A1

1000.0-0000.0

0A

CPA-1A1

1000.0-0000.0



41

SAE 4640

0.0128-0.0192

42

SAE 4640

0.0192-0.0256

12

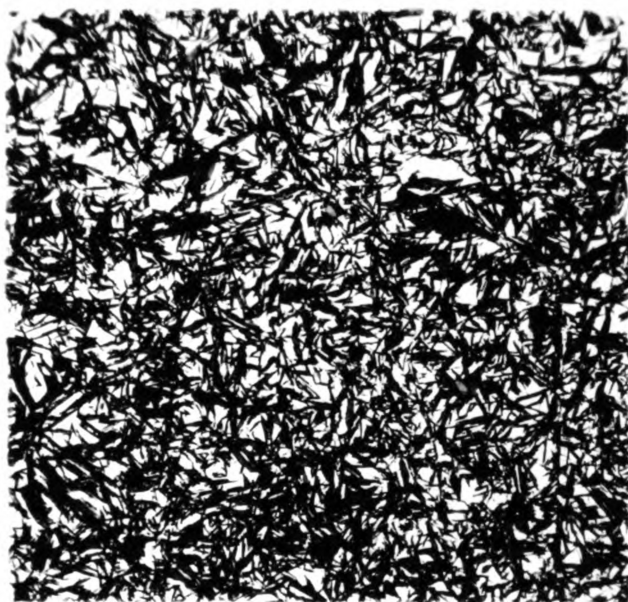
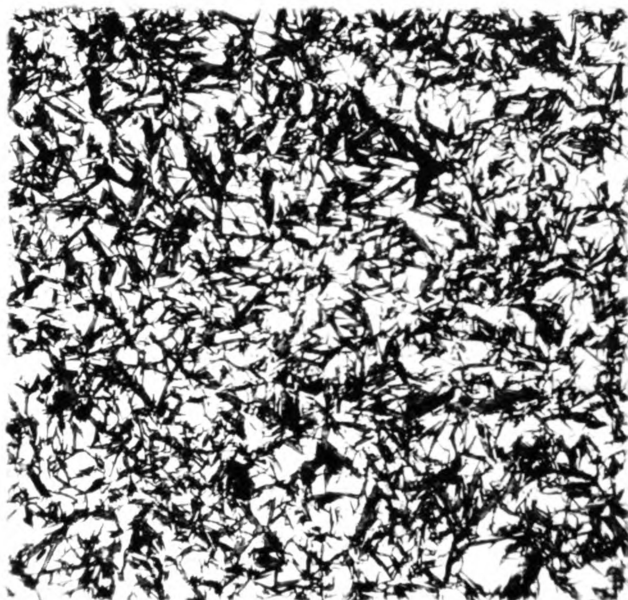
0000-111

0000-111

12

0000-111

0000-111



43

SAE 4640

0.0256-0.0320

44

SAE 4640

0.0320-0.0384

24

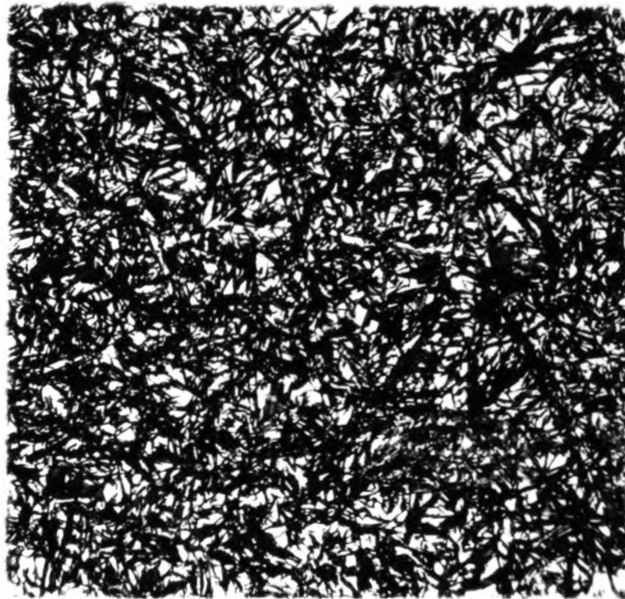
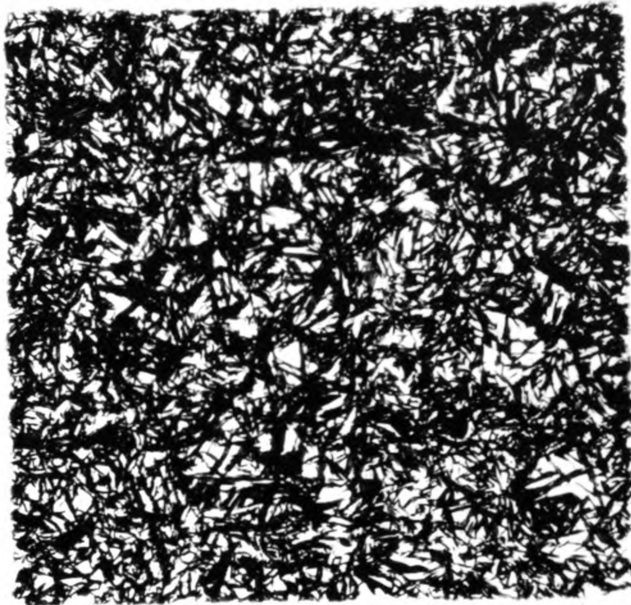
0402-112

0430.0-5830.0

24

0402-112

0430.0-5830.0



24

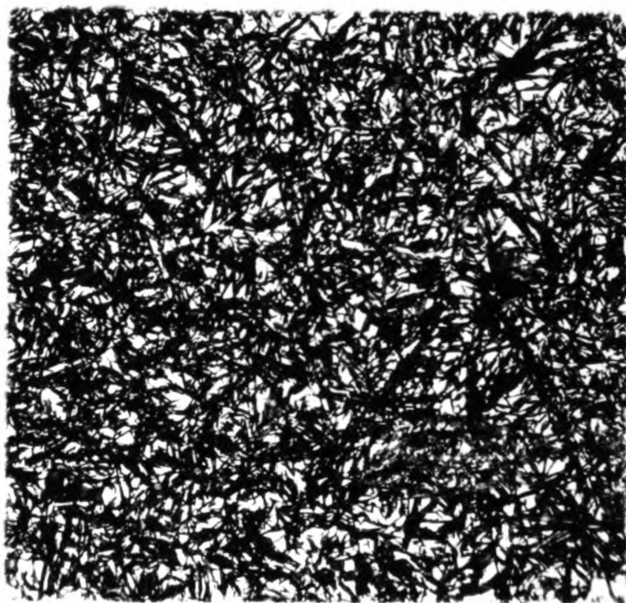
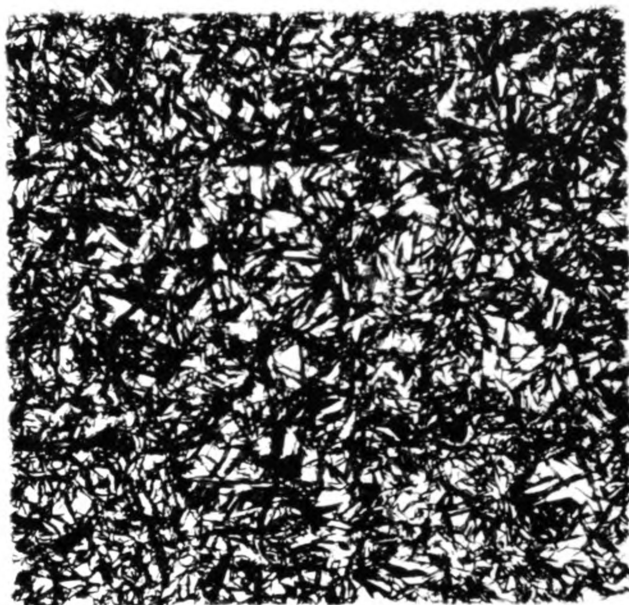
0402 1:2

0500.0-0500.0

24

0402 1:2

0500.0-0500.0



45

SAE 4640

0.0384-0.0448

46

SAE 4640

0.0448-0.0512

80

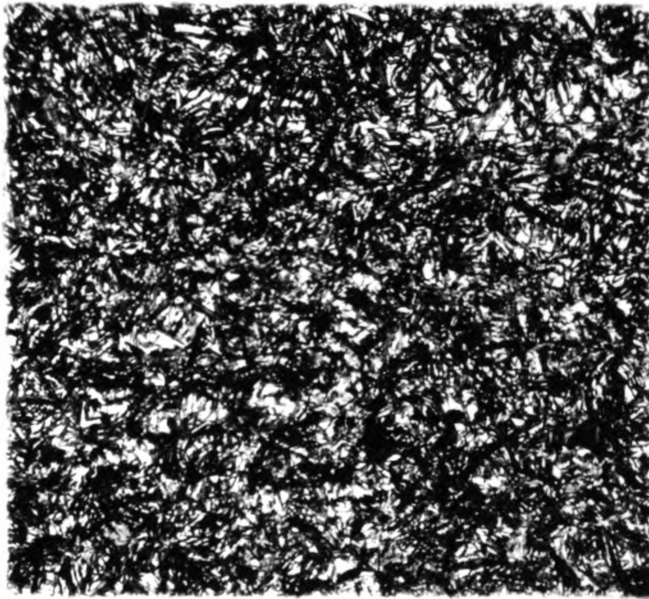
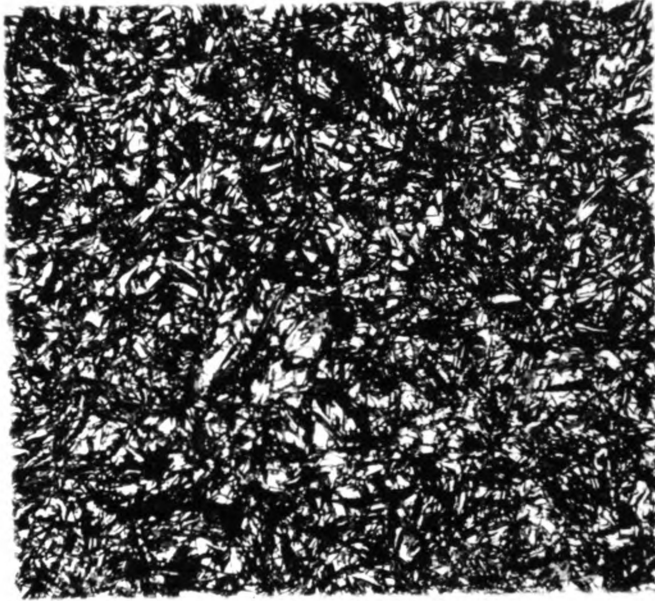
0000 111

0000.0-0000.0

80

0000 111

0000.0-0000.0



47

SAE 4640

0.0512-0.0576

48

SAE 4640

0.0576-0.0640

72

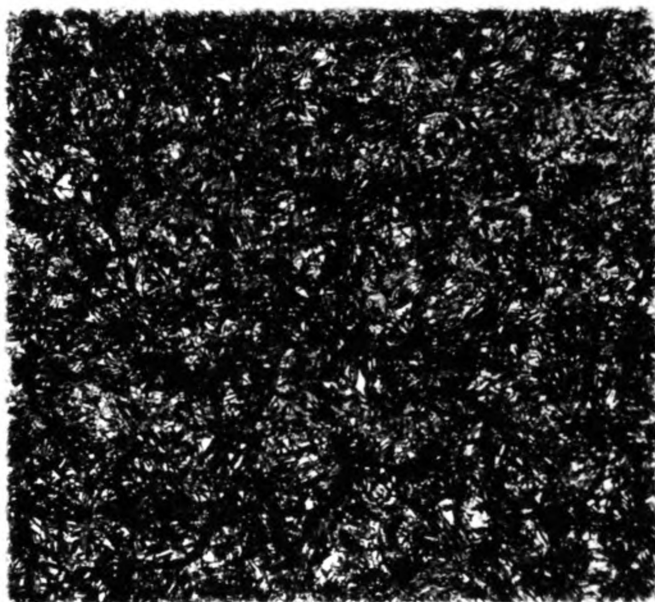
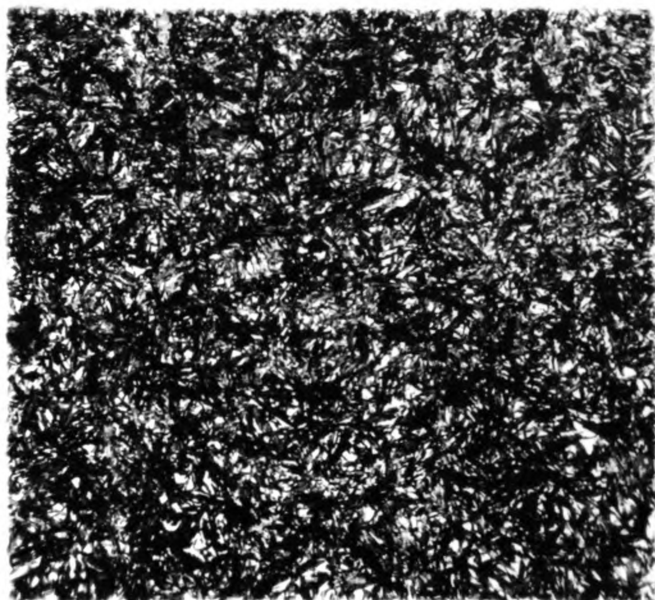
OPPA and

0.0010-0.0010

84

OPPA and

0.0010-0.0010



49

SAE 4640

0.0640-0.0704



Table 8

Jominy Bar Data

All Bars $\frac{1}{2}$ " Except Those Designated Otherwise

(Hardness- R_C)

<u>Distance From Bar End</u>	<u>SAE 1010</u>	<u>SAE 2015</u>	<u>SAE 2340</u>	<u>SAE 3145</u>	<u>SAE 4640</u>	<u>SAE 4640(1")</u>
1(16ths)	58	56.5	46	53	55	63
2	59	58	48	56	56	62
3	55	59	50	55	57	62
4	47	58	50	56	58	62
5	46	58.5	50	56	58.5	62
6	45	57	49.5	56.5	59	62
7	45	55	49	57	59	61.5
8	44	52	49	57	59	61.5
9	43.5	49	49.5	57	59.5	61
10	42.5	46	50	55.5	60	61
11	42.5	44	49.5	55.5	60	60
12	43.5	43	49.5	56.5	60	59.5
13	43.5	43	51	56	60	59
14	43.5	42.5	51	54.5	60	59
15	43	44	51	55.5	60.5	58
16	42	43	51	56.5	60	57
17	42	44	51	54.5	60	56
18	42	45	52	55	59.5	55.5
19	41	45	51.5	54.5	59.5	54
20	41	44	51	55	58.5	52
21	41	43	51	58	58	51

Continued On Next Page

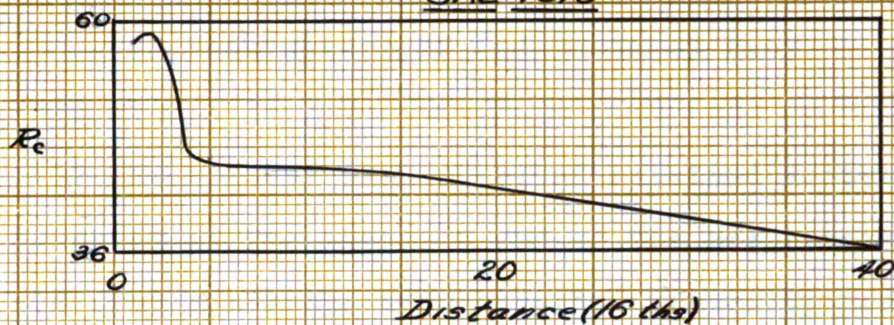
Jominy Bar Data

(Continued)

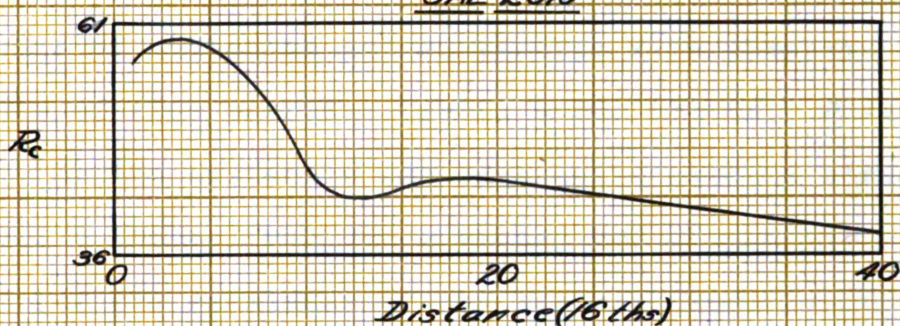
<u>Distance From Bar End</u>	<u>SAE 1010</u>	<u>SAE 2015</u>	<u>SAE 2340</u>	<u>SAE 3145</u>	<u>SAE 4640</u>	<u>SAE 4640(1")</u>
22	41.5	43	50.5	58	56.5	51
23	41	42	51	54	55	50
24	40.5	42	51	55	52.5	49.5
26	39.5	42	51.5	55.5	50	48
28	39	41.5	51.5	55	49	47.5
30	38	41	52	55	48	46
32	37.5	40	52	54.5	44.5	45.5
34	36.5	39	52	54.5	43.5	45
36	36.5	39	52	55.5	43	45
38	35.5	39	53	54.5	40.5	44.5
40	36	38	53.5	54.5	40	43

FIGURE 8
GRAPHS OF JOMINY DATA
HARDNESS R_c vs. DISTANCE FROM END OF BAR
($\frac{1}{2}$ " Bars - Carburized)

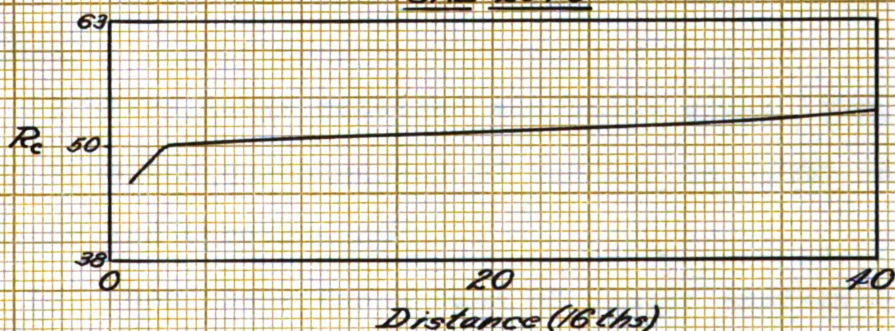
SAE 1010



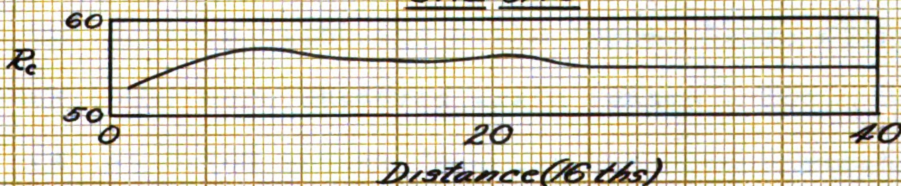
SAE 2015



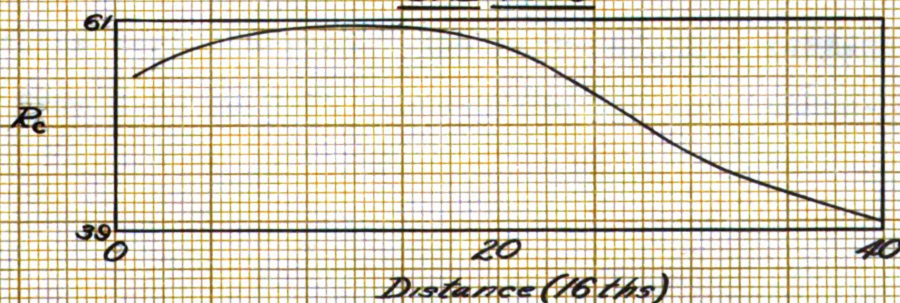
SAE 2340



SAE 3145



SAE 4640



Part II (c)

Microstructure of End-quenched Bars

SAE 1010

(1) The highest percentage of retained austenite was observed at the quenched end of the bar (photo - 59).

(2) The austenite concentration gradually decreased until at 0.150 inches from the quenched end of the bar patches of austenite and martensite were observed in a matrix of fine pearlite (photo - 58) (photo - 60).

(3) The austenite and martensite patches disappeared at 0.375 inches from the quenched end of the bar.

(4) The remainder of the bar was pearlite in varying degrees of coarseness.

SAE 2015

(1) Very large retained austenite areas (50%) were found from the quenched end of the bar to 0.090 inches from the end (photo - 50)

(2) Then there was a band of lesser austenite concentration between 0.090 and 0.150 inches (photo - 51).

(3) Between 0.150 and 0.210 inches large austenite patches (50%) were observed again (photo - 52).

(4) At 0.700 inches from the quenched end patches of combined austenite and martensite surrounded by fine pearlite were observed. The range of this formation was from 0.50 to 0.75 inches from bar end (photo- 53).

(5) The area between 0.210 and 0.500 inches contained scatterings of small austenite areas.

(6) At 0.940 inches from the quenched end distinct carbide networks were observed and these networks continued, in varying degrees, to the end of the bar. The cementite network began when the austenite-martensite patches disappeared.

SAE 2340

(1) Retained austenite was quite constant, up the bar from the quenched end, with regard to quantity and size of areas to 0.50 inches (photo - 54).

(2) At 0.50 from the quenched end there was a slight indication of carbide network formation (photo - 55).

(3) The retained austenite disappeared almost completely when the carbide networks became quite pronounced at 1.50 inches (photo - 56).

SAE 3145

A trace of retained austenite was observed at the extreme quenched end of the bar only. This was the only position at which any austenite was observed (photo - 8).

SAE 4640

(1) There was a gradual decrease in the size of the austenite areas from the quenched end to the 1.310 inch position, at which point the carbide networks appeared (photo - 61) (photo - 62).

(2) Between 1.310 and 2.625 inches from the quenched end the carbide network persisted.

(3) At distances greater than 2.625 inches, there was pearlite in varying degrees of coarseness.

Part II Photomicrographs

The photomicrographs in this section represent steels that were all subjected to the following treatment and specifications.

1. Carburized for 13 hours at 1700 deg. Fahr.
2. End quenched in a 0.25 inch stream of water
3. All steels were then tempered at 400 deg. Fahr.
for a period of 1.5 hours
4. Etchant- 3% nital
5. Longitudinal section
6. Magnifications 500 X
7. The number of the photomicrograph, steel, and distance from the quenched end will be listed, in that order, on the page just proceeding each set of pictures.

50

SAE 2015

0.070" from end

51

SAE 2015

0.120" from end

52

SAE 2015

0.180" from end

02

0103 11.1

0.100" from end

01

0103 11.1

0.100" from end

02

0103 11.1

0.100" from end



53

SAE 2015

0.690" from end

54

SAE 2340

0.125" from end

55

SAE 2340

0.810" from end

63

0100 142

One more "0100.0"

64

0100 142

One more "0100.0"

65

0100 142

One more "0100.0"



56

SAE 2340

1.500" from end

57

SAE 3145

0.018" from end

58

SAE 1010

0.155" from end

RE

0101 111

0101 111 111.0

RE

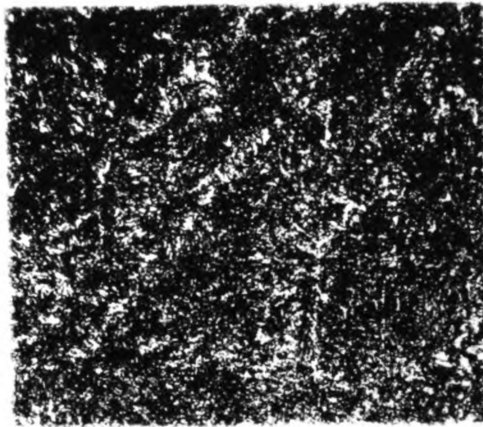
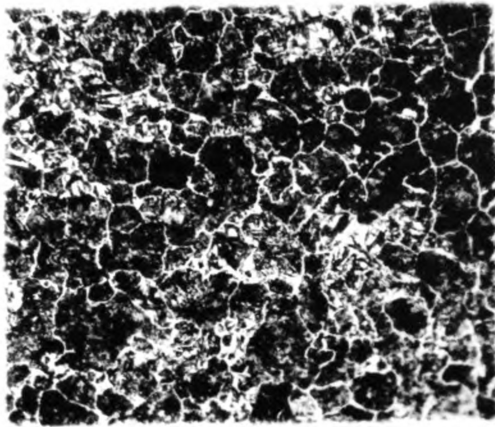
0101 111

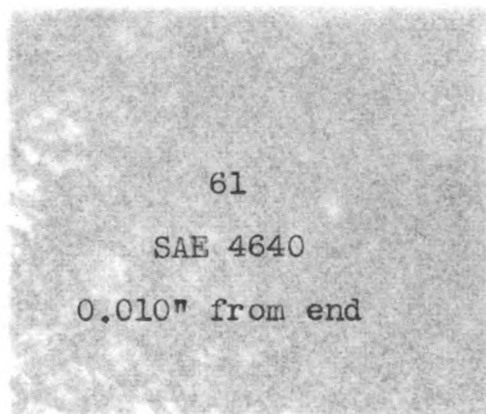
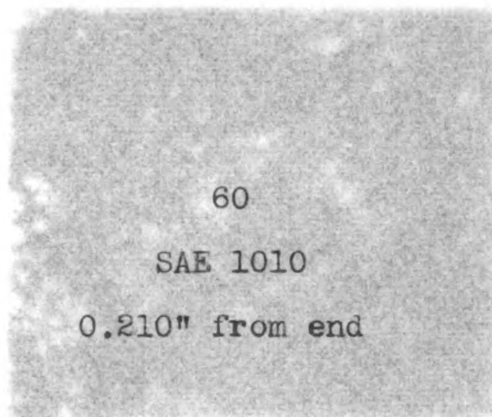
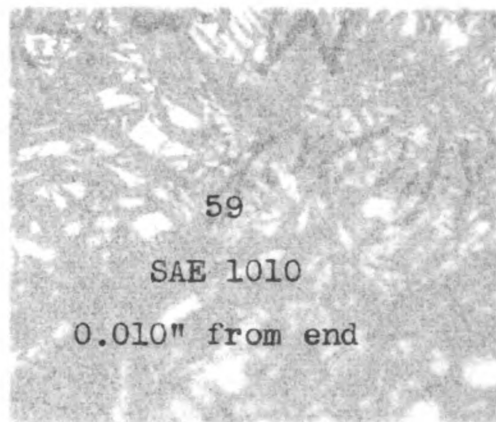
0101 111 111.0

RE

0101 111

0101 111 111.0





95

1941-1942

One more "111.0"

OR

1941-1942

One more "111.0"

19

1941-1942

One more "111.0"



93

0101 844

0.0101 100.0

04

0101 844

0.0101 100.0

16

0004 144

0.0004 100.0

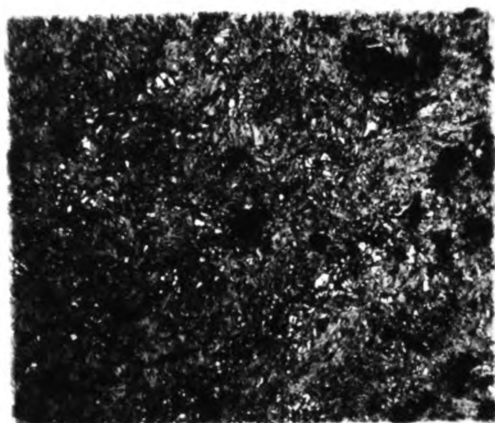


62

SAE 4640

1.310" from end

NO
111 404
I. 111. 111 404



Part III Photomicrographs

The photomicrographs in this section represent steels that were all subjected to the following treatment and specifications.

1. Carburized for 13 hours at 1700 deg. Fahr.

2. Quenched from 1700 deg. Fahr. in

Water- SAE 1010

Oil- SAE 2015

3. Etchant- 3% nital

4. Transverse section

5. Magnifications 500 X

6. The number of the photomicrograph, steel, and the tempering temperature (deg, Fahr.) will be listed, in that order, on the page just preceding each set of pictures.

63

SAE 1010

350° F.

64

SAE 1010

400° F.

65

SAE 1010

425° F.

NO
1918
F. 1918

NO
1918
F. 1918

NO
1918
F. 1918



66

SAE 1010

440° F.

67

SAE 1010

450° F.

68

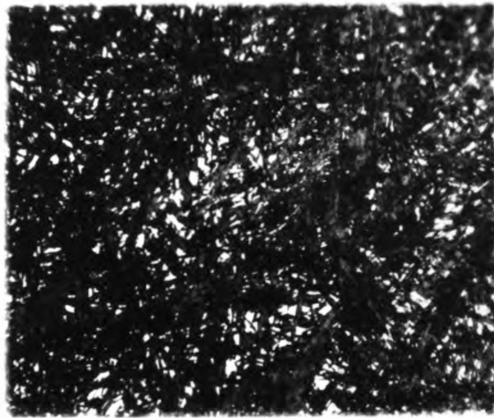
SAE 2015

430° F.

TO
CHIEF AND
F. O. LIAISON

TO
CHIEF AND
F. O. LIAISON

TO
CHIEF AND
F. O. LIAISON



Discussion

During the experimental work some doubt had arisen as to whether or not the light constituent, in the photomicrographs was actually retained austenite. It was thought that this light etching material might have contained untempered martensite. The best results obtained as far as proving that the light etching material was actually austenite, was obtained from work done on varying the tempering temperatures of sections of SAE 1010 carburized steel, that contained appreciable quantities of light material in the microstructure. Another indication was obtained by correlating the microstructure of the polished flats on the 0.5 inch end quenched bars to the Rockwell-C values obtained on the same surface.

The work on tempering of carburized SAE 1010 steel was done by obtaining five pieces of the steel all containing approximately the same quantity of the light etching constituent. These samples were then tempered at varying temperatures between 350°F. and 450°F. and it was observed, as was shown in the photomicrographs of Part III, that little change occurred in the light areas until 440°F. was reached, where there was appreciably less white constituent than at 425°F. At 450°F. only very slight traces remained. This transformation was quite in agreement with Bain's work (7), as he claimed

a transformation temperature of austenite in plain carbon steels at 455°F.

As was mentioned before an indication of retained austenite was obtained in the 0.50 inch bars of end quenched SAE 1010, SAE 2015, and SAE 4640 steels. The curves of these steels (Figure 8) showed a definite correlation between the areas of greatest retained austenite and the Rockwell hardness. On the other hand, SAE 2340 and SAE 3145 gave results that were definitely not expected in view of their microstructures. As an example, the SAE 4640 gave a Rockwell-C reading of 6 points lower at the quenched end where the cooling rate was the highest, than at a position .810 (approximately) inches from the quenched end. This was definitely abnormal for the end-quenched curve and thus indicated that the light etching material must have been somewhat softer (austenite) and caused this abnormality.

Rockwell-C and file hardness tests were also taken on the quenched rounds of Part I. These results were discounted because Rockwell-C values were taken instead of Rockwell superfical, and it was thought that the Rockwell-C "brale" might have penetrated the case instead of revealing the surface hardness. The file hardness test showed that the surface of the steel in every case was

softer than the file. This could mean that the case contained retained austenite or that the tempering treatment at 400°F. made the steel softer than the file.

The photomicrographs were observed in Part I and it may be said that the higher the carbon contents, up to the maximum of the surface, the more the tendency for the retention of austenite. It cannot, however, be said directly that the microstructures of Part I give a direct indication of the amount of austenite at a definite carbon content because other factors were involved. One of the factors was the difference in quenching rate from the surface to the center of the round quenched. The quenching media had a definite effect in the amount of austenite obtained. All in all, in quenching a carburized round, two variables will always be involved and therefore both must be considered in evaluating the data obtained by this method.

If the photomicrographs in Part I are observed, it will be noted that the retained austenite seemed to decrease on the very edge. This was caused by a slight decarburization which either occurred during the carburization or later when the samples were heated in used carburizer to be quenched. Two of the steels showed decarburization in their carbon gradients (SAE 3145 and SAE 4640).

The carbon gradient curves had to be weighted in order that they would present somewhat of a smooth curve for comparison with the corresponding photomicrographs. Several points strayed from the general trend of the carbon curves and upon repeating the run, similar inconsistencies were encountered. The inconsistencies were probably due to inhomogeneities in the carburized layers involved and also due to the extreme difficulty in collecting the "oil free" chips. The values obtained should have been quite close inasmuch as extreme care was exercised in repeating the procedure very exactly each time a run was made.

The retained austenite in any one layer or carbon content in the carburized sections of Part I varied considerably as the piece was revolved. When the photomicrographs were made for Part I, this was taken into consideration and an average or representative point was chosen in every case. The same inconsistency arose on the flats of the end-quenched bars but in this case, observations were made down the center of the polished flats. These discrepancies probably occurred due to differences in the carburized cases and also they may have been due to an inhomogeneous austenite before quenching. The latter explanation was very possible due

to the fact that an austenitizing temperature of only 1700°F. was used and the time at temperature was as short as possible to prevent undue decarburization.

In Part III, it was found if several pieces of the same carburized steel were subjected to varying tempering temperatures that the inherent inhomogeneous structure caused differences in the results obtained. This was not true of the 450°F. temperature because practically all of the retained austenite was transformed throughout the complete sample. However, at lower tempering temperatures, errors could have very easily crept into the work by using poor judgement in choosing the area to photograph. The tempering effect could have been observed more accurately by using one piece of steel and one area, and this area could have been photographed at small temperature increments starting at 350°F. and continuing until 450°F. had been reached. Tempering time had a definite effect upon the amount of transformation especially in the temperatures around 450°F. and for this reason it was imperative that constant tempering times were used to insure any comparison whatsoever.

The microstructures of the end-quenched bars in Part II seemed to indicate that the higher the quenching rate, the greater the quantity of retained austenite. Previous work

has shown, on cooling rates, that there is a region near the critical cooling rate, which gives rise to more retained austenite, and this has been used to explain, in some degree, the greater retained austenite in oil quenched parts than in the same parts water quenched. Only the SAE 2015 steel gave an indication of the fact that there may be certain cooling rates less susceptible to the retention of austenite. A transverse banding of retained austenite in the bar was observed along its length. From the quenched end to 0.090 inches from the quenched end existed a dense mass of austenite, then there was a band of lighter austenite concentration between 0.090 and 0.150 inches, past which large austenite particles were observed and these gradually tapered off at a distance of 0.70 inches (approximately) from the quenched end of the bar. The area seemed too well defined to be considered an inhomogeneous segregation although it was not an impossibility. Some error was undoubtedly introduced when the copper was removed from the flats by hand honing and for this very reason, no definite statements can be made other than the close relation of the hardness curve to the microstructure. The error, although probably only a few thousandths of an inch, may have meant a difference in carbon content of 5 to 20 points. The microscopic data

obtained in Part II had to be correlated to relative cooling rates within the bars because of a lack of high speed temperature recording equipment. The 1.00 inch SAE 4640 bar was run in an effort to try and link up to its known cooling rate that in a corresponding 0.50 inch bar of the same steel. The only comparison that was possible was that between the points on each bar where the carbide network just began to form. After a very careful microscopic examination of each bar, it was decided to throw out this means of getting at the cooling rate, due to the wide discrepancy in the starting point of the carbide network.

Another method was used to try and correlate the quenching rates of the 0.50 inch and 1.00 inch bars by the use of previous data obtained on SAE 4063. By graphing cooling rate (ordinate) vs. distance from the quenched end (abissa) for the SAE 4063 steel, it was found that the curves were extremely hard to interpret as such, and that before a comparison could be made it would be necessary to have more data particularly on the steels used in this experiment.

Metallographic methods (16) are not the only means of getting at the amount of retained austenite in a steel sample. As a matter of fact, there are several methods much more satisfactory but again, a lack of time

and equipment formed a barrier to a possible check on the results obtained. The determination of retained austenite has been done by magnetic methods, X-ray methods, specific volume changes, electrical resistance methods, dilatometric methods, and micro-hardness determinations.

An effort was made to link retained austenite with the M_f temperatures of the five steels used in the experiment. After several calculations were made, it was found that the M_f temperature in the high carbon high alloy steels fell below that of room temperature. The M_f temperatures for plain carbon steels of a similar carbon content were found to come quite close to that of room temperature. Lower carbon contents caused the M_f temperature to fall above room temperature. The data used in the calculations (17) showed quite a wide discrepancy and this had to be considered in the calculation of M_f temperature. It was observed that the plain carbon steels contained the least retained austenite while the higher alloy steels exhibited the most retained austenite in a similar carbon content layer of Part I. This phenomenon might have had some bearing on the fact that the higher carbon contents showed more retained austenite, and that it was necessary for the carbon content to be quite high in order to have the M_f temperature fall below room temperature. Also correspondingly lower carbon contents exhibited the same retained austenite percentage in alloy steels

as compared to the plain carbon steel, this being due to the effect of the alloying elements on the M_f temperature.

Conclusions

1. Higher carbon contents promoted the retention of greater quantities of austenite, all other factors remaining constant.
2. The retention of austenite is not always the greatest at the critical cooling rate. This was indicated by the alternate bands of retained austenite in the SAE 2015 (end-quenched), with a band of very little austenite between them.
3. The light etching constituent austenite was completely transformed into one of its transformation products, in a plain carbon steel, at about 450^o F. if sufficient time was used during tempering.
4. Retained austenite appeared to transform, upon tempering, over a range of temperatures rather than at any single temperature.
5. The higher alloy steels retained more austenite upon quenching than did the plain carbon steels.

Possible Future Work

More work should be done in the future on the end-quenched bars. It is felt that if a means of determining the exact cooling rates within the bars during quenching were made available some interesting data could be obtained in connection with the work on retained austenite.

A means of determining more correctly the effect of increased carbon content could be obtained by quenching, in the same media, several thin strips of the same steel, carburized to different carbon contents. By using thin strips the variable caused by the quenching rate could be completely eliminated. In this connection, strips of the same carbon content could be quenched in different medias to determine the effect of varying quenching rates upon the same section of a similar steel.

Also some work should be done in the future regarding the effect on the retention of austenite of quenching from higher temperatures in the austenite range.

Selected References

1. Metals Handbook, 1939 Edition, American Society for Metals, Cleveland, Ohio
2. G. V. Smith and R. F. Mehl: "Lattice Relationships in Decomposition of Austenite to Pearlite, Bainite, and Martensite," Metals Technology, April, 1942
3. A. B. Greninger and A. R. Troiano: "Crystallography of Austenite Decomposition," Metals Technology, August, 1940
4. E. C. Bain: "Alloying Elements in Steel," American Society for Metals, Cleveland, Ohio, 1939
5. Samuel Epstein: "The Alloys of Iron and Carbon," Vol. I Constitution, McGraw-Hill Book Co., 1936
6. S. G. Fletcher and M. Cohen: "Subatmospheric Transformation of Retained Austenite," American Society for Metals Transactions, Volume 34, 1945
7. E. C. Bain: "Alloying Elements in Steel," American Society for Metals, Cleveland, Ohio, 1939
8. H. J. French: "Alloy Constructional Steels," American Society for Metals, Cleveland, Ohio, 1942
9. D. P. Antia, S. G. Fletcher, and M. Cohen: "Structural Changes During the Tempering of High Carbon Steel," American Society for Metals Transactions, Vol. 32, 1944

10. C. A. Liedholm: "Retained Austenite and Its Decomposition Range in a Quenched Cobalt High Speed Steel," American Society for Metals Transactions, 1935
11. F. Wever and N. Engel: "Über den Einfluss der Abkühlungsgeschwindigkeit auf die Temperatur der Umwandlungen, das Gefüge und den Feinbaud der Eisen-kohlenstoff-Legierungen"(Effect at Cooling Velocity on the Temperature of Transformations and the Structure of Iron-Carbon Alloys), Mitt. K - W. Inst. Eisenforschung, v. 12, 1930 pp. 93-114
12. E. S. Davenport and E. C. Bain: "Transformation of Austenite at Constant Subcritical Temperatures," Trans. Am. Inst. Min. Met. Eng., vol. 90, 1930, pp. 117-154
13. H. Esser and H. Cornelius: "Die Vorgänge beim Anlassen abgeschreckter Stähle"(Occurrences during the Tempering of Quenched Steels), Archiv f. d. Eisenbuttenwesen, v. 7, 1934
14. G. Tammann and E. Scheil: "Die Umwandlungen des Austenits und Martensits in gehärteten Stählen" (The Transformations of Austenite and Martensite in Hardened Steel), Z. anorg. allgem. Chem., v. 157, 1926
15. K. Tamaru and S. Sekito: "On the Quantitative Determination of Retained Austenite in Quenched Steels," Sci. Rep., Sendai, ser. 1, v. 20, 1930

16. P. Gordon, M. Cohen, R. S. Rose: "The Kinetics of Austenite Decomposition in High Speed Steel," American Society for Metals Transactions, Volume 31, 1943
17. R. A. Grange and H. M. Stewart: "The Temperature Range of Martensite Formation," Metals Technology, June, 1946

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