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A PHYSICAL AND MICROGRAPHICAL STUDY
OF CARBON STEELS

Thesis for the Degree of B. S.

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1921



A PHYSICAL AND MICROGRAPHICAL STUDY

of

CARBON STEELS

A Technical Report Submitted to

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by

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and

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Candidates for the Degree of

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THESIS

PREFACE

In view of the fact that the subject of Carbon Steels has been thoroughly worked out by a number of experienced men, and that information on this subject is available from a number of sources, one may think it queer that we should select it for our Technical Problem.

Our aim, however, was to obtain a greater knowledge of the subject of Carbon Steels through our own original work, and now that the work is completed, we feel that the experience which we gained in the machine shop, heat treating shop, micrographical laboratory, and testing laboratory has been an ample reward for our energy.

We are greatly indebted to Mr. Walter Hildorf and Mr. Charles Thomas of the Rec Motor Car Co. and to Mr. C.H. Stuart of Dodge Brothers for their aid in furnishing us with materials. We also wish to thank Mr. Baker, Mr. Publow, and Mr. Rueling of the Michigan Agricultural College for their valuable suggestions,

A.V. Aronson.

H.L. Broan.

East Lansing, Michigan, June 8th, 1921.

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INTRODUCTION.

Steel is one of the main materials with which the civilized world has to deal in the present era. The manufacture of steel has increased immensely during the past century, due the increased demand for it and to the improved processes which have enabled the manufacturers to meet this demand.

The two main constituents of steel are carbon and iron, - the percentage of the latter being about 99%, in the plain carbon steels. Besides these two, there are found a number of other elements, which are termed impurities. These are varying amounts of silicon, manganese, phosphorus, sulphur, and traces of many other metals and metalloids. All grades of steel contain a trace at least of silicon, and occasionally as much as 0.5%, though most grades contain between 0.05 and 0.3%.

Manganese is found in steel in combination with either sulphur or carbon in the form of manganese sulphide (MnS) or carbide of manganese (Mn_3C). The percentage of manganese varies from .25 up to as high as 1.0%. Steel of satisfactory quality contains from a trace to .15% Phosphorus, which is held in solid solution by the iron as the phosphide of iron (Fe_3P). When the phosphorus content ^{over} .1%, it has a marked tendency to increase the grain size of the metal, thereby increasing the brittleness. Sulphur should never occur in steel in excess of .1%, - the content usually being .01 to .05%. It occurs chiefly in the form of iron sulphide (FeS) and manganese

sulphide (MnS).

The alloy steels contain other elements in addition to those named above. The most common alloy steels are nickel, nickel-chrome, chromium, chrome-vanadium, and silico-manganese. These contain the elements which their names suggest.

In plain carbon steels the carbon content varies from .01 to about 1.70%, iron containing more than this amount of carbon being termed cast iron. The properties vary with the amount of carbon, and in this paper we have tried to show some of these outstanding differences.

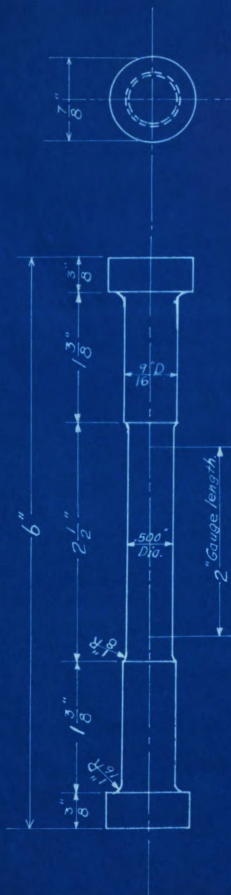
PHYSICAL ANALYSIS.

There are a number of points to be considered in the physical analysis of a sample of steel. Among these, the most important are the tensile and torsional tests. In this work, however, we intend to show only the tensile properties of a number of samples of plain carbon steels varying from a very low to a very high carbon content. In order to do this, it was necessary to assemble data for the following curves:

1. Elastic limit
2. Maximum strength
3. Modulus of elasticity
4. Elastic resilience
5. Reduction of area
6. Elongation
7. Hardness

The samples of steel which were tested were 7/8" rolled steel bars, and in order to bring them all to the same conditions before making any tests, it was necessary to normalize them. This was done by heating them to 1700 ° F and allowing them to cool slowly in the furnace, for about twenty-four hours. After the samples had cooled, they were turned into test bars, - four bars being made of each sample.

The hardness was taken of each test bar both before and after normalizing. The readings taken before heat treating were not consistent with the carbon



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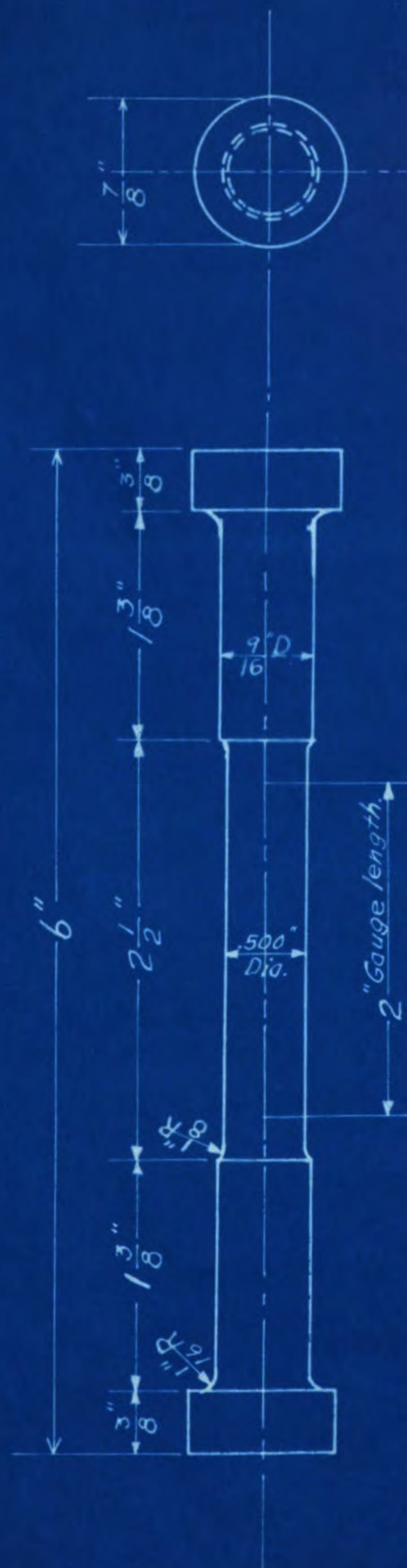
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content, due to the fact that the samples came from a number of different mills and probably did not receive the same annealing treatment. The readings taken after the bars were normalized show that the hardness increases uniformly with the increase in carbon content.

In pulling the test bars, a 120,000 Whiele testing machine was used. A Berry strain gauge was attached to the two punch marks in order to show the elongation. The load was applied in 1000 pound increments until near the elastic limit, and then it was applied in 500 pound increments. The elongation was read from the Berry strain gauge at each increment. When the elastic limit had been passed, the gauge was removed and the load was increased until the test bar broke.

The data thus obtained was used in plotting a stress-strain diagram, from which we were able to read the elastic limit and the unit deformation. The diameter and the length between the punch marks was taken before and after breaking, which data enabled us to compute the reduction in area and the elongation. The unit stress at the elastic limit, the maximum strength, the modulus of elasticity, and the elastic resilience were then computed from these data. All of these data and a sample of the computations will be found following this discussion.

The accompanying curves show the results

FIG. 1

CURVES SHOWING RELATION B
MAXIMUM STRENGTH, ELASTIC
AND CARBON CONTENT.

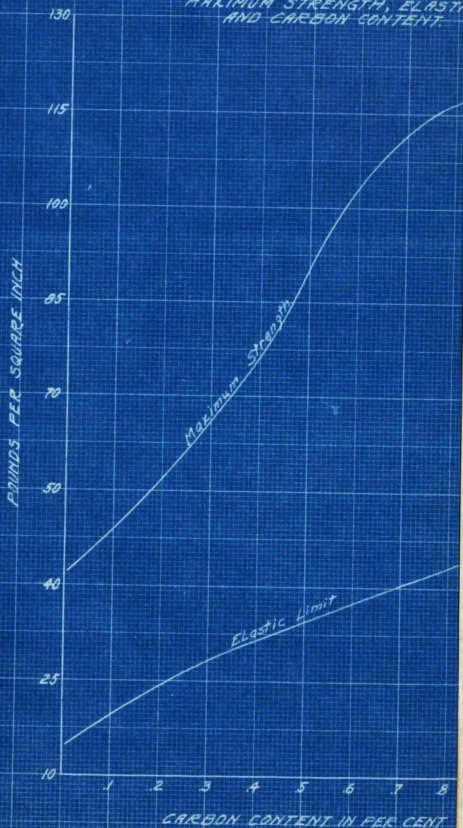
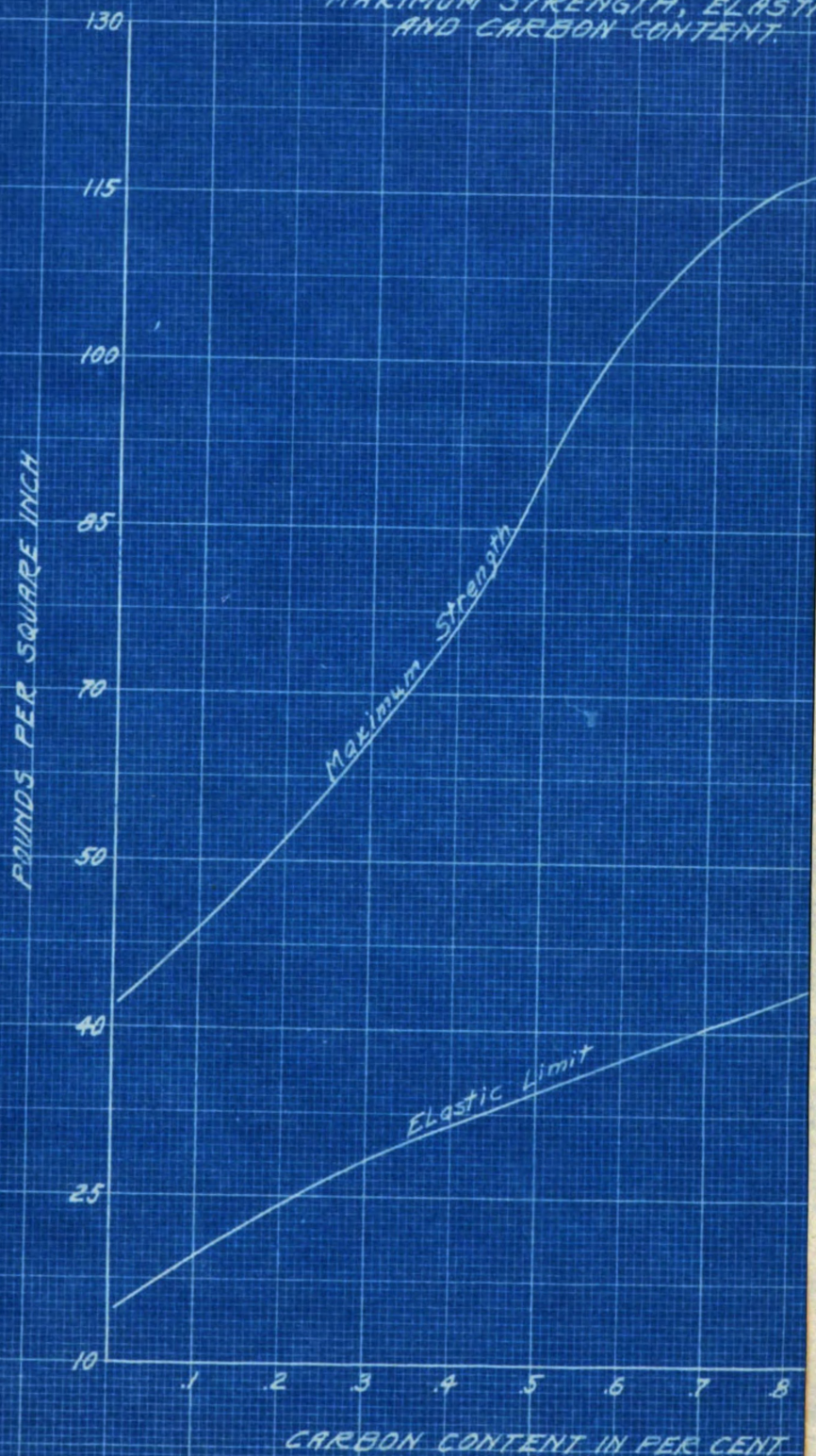


FIG. 1.

CURVES SHOWING RELATION B.
MAXIMUM STRENGTH, ELASTIC
AND CARBON CONTENT.



5.

of our tests. Figure 1 shows how the elastic limit and the maximum strength vary with the carbon content. The points were determined by taking the average of the four test bars in each sample.

Let us first consider the elastic limit curve. The unit stress at the elastic limit increases uniformly and gradually for the steels having a carbon content of from .8 to .9%, and below and above these points the increase is not quite uniform, but is a little more rapid. It is plainly evident from this curve that if a piece of steel were to be selected for strength alone, the carbon content should be high.

The other curve shows that the maximum strength increases more rapidly than the elastic limit until the eutectoid point is reached. For hyper-eutectoid steels, however, the maximum strength decreases. The fact that these two curves do not have the same slope show that the elastic ratio, which is the unit stress at the elastic limit divided by the maximum unit stress, decreases with the increase in the carbon content up to the eutectoid point.

Figure 2 shows the curves for the modulus of elasticity and the elastic resilience. The former remains practically constant at a little above 30,000,000. However, for the sample containing .011% carbon, it is much lower, being 18,700,000. This sample is, as you will notice, a practically carbonless steel, and is therefore very ductile.

FIG. 2.

CURVES SHOWING RELATION BET
MODULUS of ELASTICITY, ELASTIC R.
AND CARBON CONTENT.

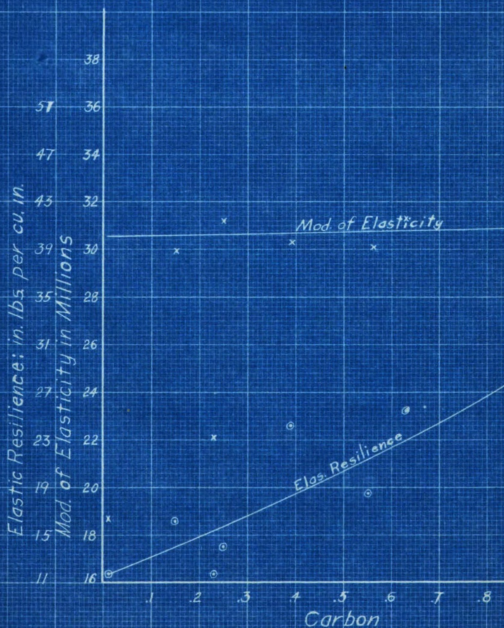
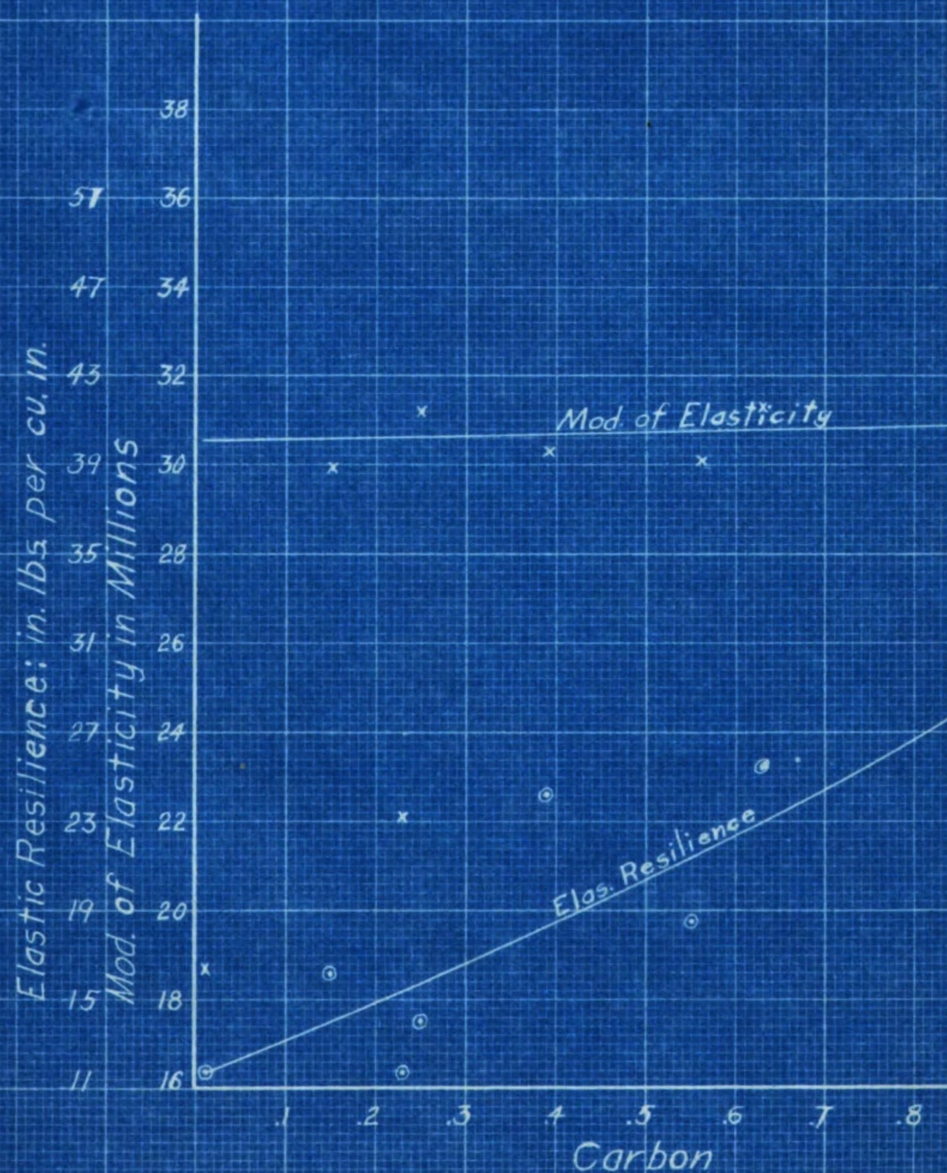


FIG. 2.

CURVES SHOWING RELATION BET
MODULUS of ELASTICITY, ELASTIC R
AND CARBON CONTENT.



6.

The elastic resilience increases quite uniformly with the increase in the carbon content. Resilience is the work which a body can do in springing back after a deforming force has been removed, and is measured in inch-pounds per cubic inch. Hence, the curve shows that the higher carbon steels have a greater tendency to return to their normal size and shape after having been deformed.

Figure 3 shows the relation between the per cent reduction in area and the per cent elongation. It will be noticed that both of these curves decrease with the increase in the carbon content, and that they are practically the same for the eutectoid steels, diverging again after passing the eutectoid point. Upon examining the different test bars after they had been pulled, we found that the reduction in area and the elongation were more pronounced throughout the distance between the punch marks in the low carbon steels than in the medium and high carbon steels. In the medium carbon steels, these changes occurred chiefly in the "necking" section, which was about one-half inch long, and in the high carbon steels, there was no very noticeable change at all, and the fracture was practically straight across the bar.

Figure 4 illustrates the hardness of the steel. The test was made with both the scleroscope and the Brinell machine. The scleroscope curves do ^{not} conform exactly with the Brinell curves, but the general tendency

FIG. 3.

CURVES SHOWING RELATION
REDUCTION OF AREA, ELONGATION,
CARBON CONTENT.

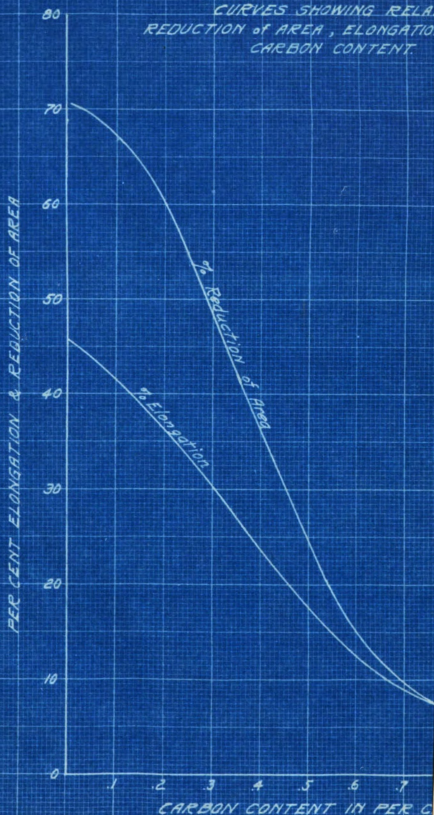


FIG. 3.

CURVES SHOWING RELATION
REDUCTION OF AREA, ELONGATION,
CARBON CONTENT.

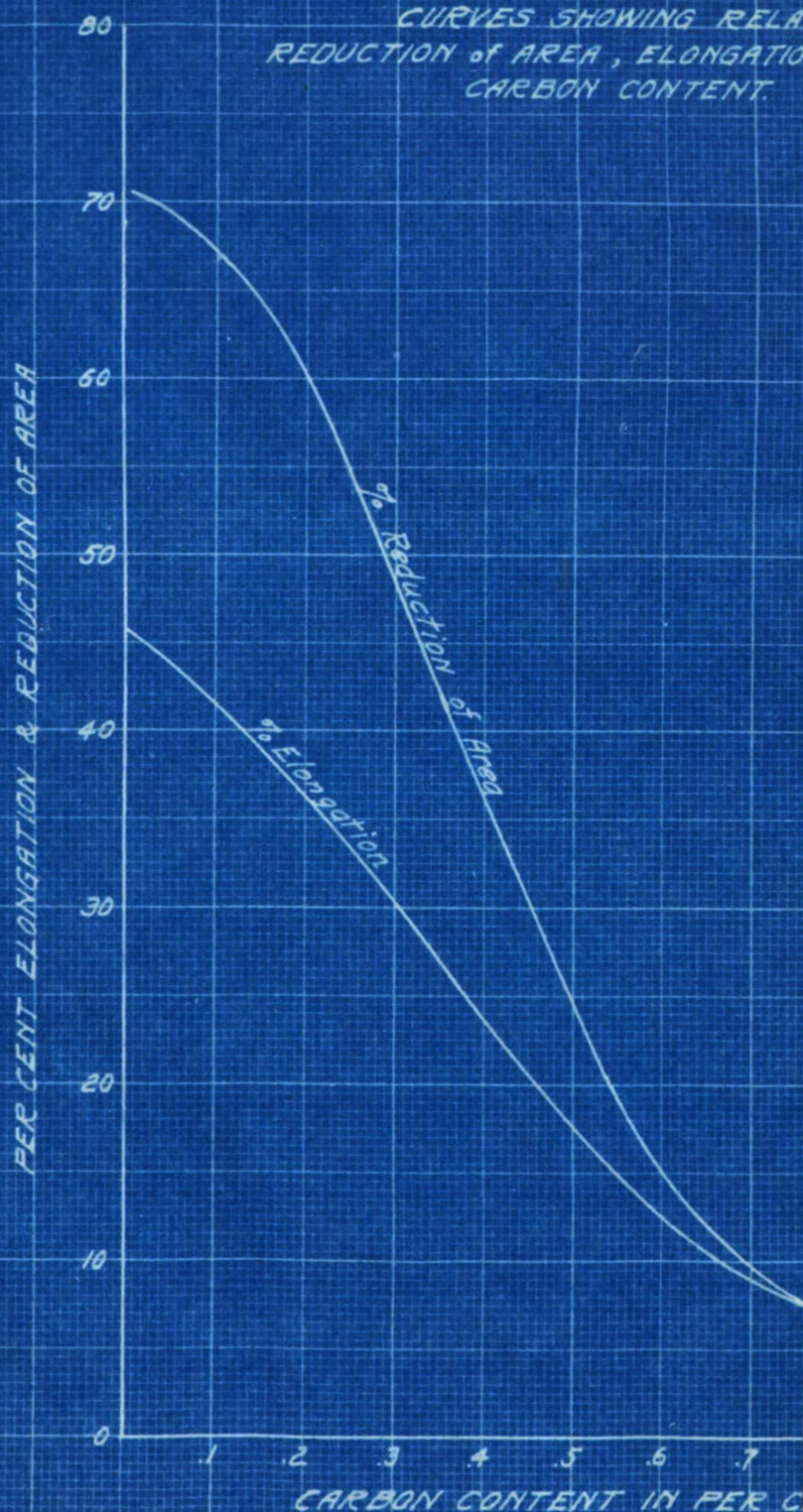
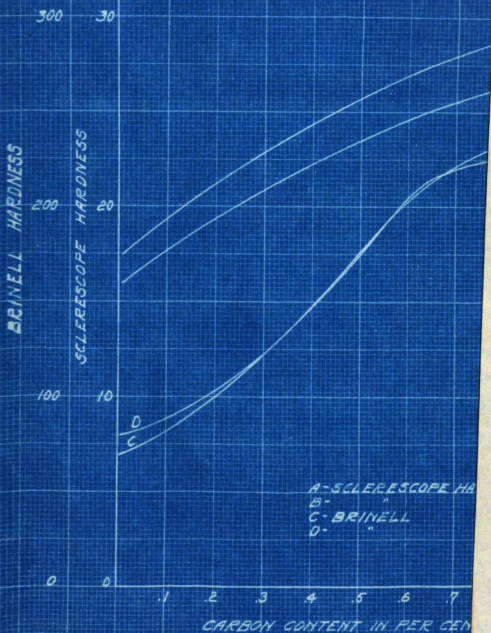


FIG. 4

CURVES SHOWING RELATION
CARBON CONTENT & HARD



A - SCLEERSCOPE HA
B - "
C - BRINELL
D - "

FIG. 4.

CURVES SHOWING RELATION
CARBON CONTENT & HARD

BRINELL HARDNESS
300 30
200 20
100 10
0 0

SCLERESCOPE HARDNESS
30
20
10
0

A-SCLERESCOPE HA
B-"
C-BRINELL
D-"

CARBON CONTENT IN PER CENT
.1 .2 .3 .4 .5 .6 .7

of all the curves is to show a marked increase in the hardness up to the eutectoid point, and from there on, the hardness seems to remain either constant or to drop slightly.

MICROGRAPHICAL ANALYSIS

In the following discussion, steel will be considered as a pure alloy of iron and carbon, free from the impurities silicon, manganese, sulphur, and phosphorus, which are always present in commercial products.

Two photomicrographs were taken of each sample, - one as received and one in the normalized condition. In normalizing, each sample was heated to 1700°F and allowed to cool slowly in the furnace for about twenty-four hours, which treatment enlarged the grain size. The samples as received were in the annealed condition, having been given a treatment which removed all internal strains caused by rolling and produced a structure that gave it maximum strength and ductility.

Steel is generally graded according to the amount of carbon it contains, and this grading is usually expressed in the following terms:

Very low carbon steel, very or extra

mild steel, very soft or dead soft steel - C not over .10%

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Low carbon steel, mild or soft

steel - C not over .25%

Medium high carbon steel, half-

hard steel - C .26 to .60%

High carbon steel, hard steel - C over .60%

Very high carbon steel, very

hard or extra hard steel - C over 1.25%

In this work, we used nine samples, -
varying in carbon content from .011 to 1.08%. However,
photomicrographs were taken of only six of these, which,
we believe, is sufficient to show the change in structure
with the change in carbon content.

Low Carbon Steels.

The first two pictures illustrate the
structure of a practically carbonless steel. The com-
mercial name of this steel is American Ingot Iron, and
it is manufactured by the American Rolling Mills Company
of Middletown, Ohio. Its main characteristic is that
it will not oxidize, and it is used considerably in
making articles which are exposed to the weather and
which do not require much strength, such as parts for
ventilating systems.

The difference between low carbon steel
and wrought iron is based upon the difference between
the methods employed for their respective manufacture
rather than upon unlike chemical or physical properties,
for these metals may indeed be quite identical both

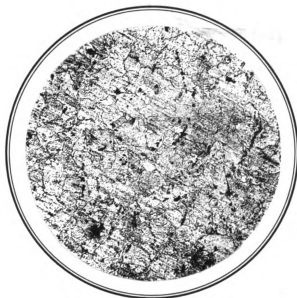
2.

physically and chemically. We may consider low carbon steel as being wrought iron from which the mechanically held slag has been removed through melting.

The pictures show that the structure consists chiefly of ferrite, but the dark lines enclosing the grains show that there is a small amount of another constituent present. (The dark spots are polishing pits. These pits are practically unavoidable in polishing such a soft specimen.) These dark lines are called "pearlite", which, when subjected to a higher magnification, are shown to consist of curved plates or lamellae alternately dark and white. We know that carbon does not exist in steel in the free state, but that it occurs in the form of carbide of iron (Fe_3C). The white lamellae consist of ferrite. Distinction is made between the ferrite contained in the pearlite and the ferrite forming the balance of low carbon steel, by calling the former "pearlite-ferrite" and the latter "free ferrite". However, it is natural to assume that free ferrite and pearlite-ferrite are identical in that they are pure iron in pure steel.

The black lamellae in pearlite, as mentioned above, are composed of carbide of iron (Fe_3C). Howe has named this carbide "cementite", and this name has been universally adopted. The atomic weights of iron and carbon are 56 and 12 respectively. Therefore cementite must contain

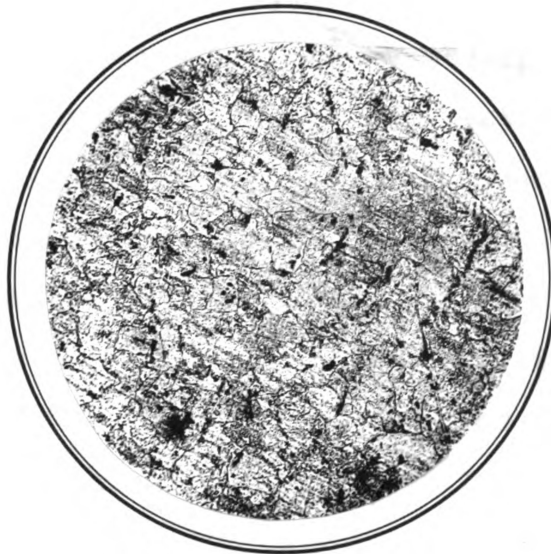
$$\frac{12 \times 100}{3 \times 56 + 12} = 6.67\% \text{ carbon}$$



.01 Carbon Steel.
Etched with HNO_3 in
 $\text{C}_2\text{H}_5\text{OH}$.
Mag. 80 x
Sample as received.



.01 Carbon Steel.
Etched with HNO_3 in
 $\text{C}_2\text{H}_5\text{OH}$.
Mag. 80 x
Heated to 1700°F and
cooled in furnace 24
hrs.



.01 Carbon Steel.
Etched with HNO_3 in
 $\text{C}_2\text{H}_5\text{OH}$.
Mag. 80 x
Sample as received.



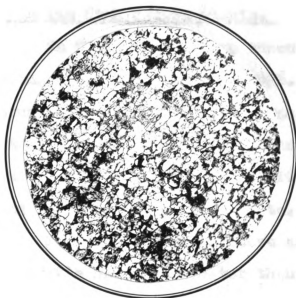
.01 Carbon Steel.
Etched with HNO_3 in
 $\text{C}_2\text{H}_5\text{OH}$.
Mag. 80 x
Heated to 1700°F and
cooled in furnace 24
hrs.

11.

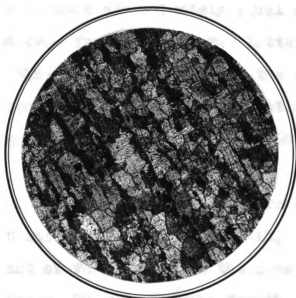
It is a very hard substance, being the hardest of all the constituents occurring in iron and steel, harder even than hardened high carbon steel. Cementite in commercial steel contains a small amount of manganese in the form of Mn_3C . Since the atomic weight of manganese is 55 and that of iron is 56, it happens that the presence of manganese in cementite has very little effect upon the carbon content. The impurities silicon and sulphur are also found in very small quantities in cementite in the form of the silicide and sulphide of iron respectively. It has been found that the presence of manganese and sulphur tend to increase the stability of cementite, and that the presence of silicon tends to decrease the stability.

As will be noticed from the photographs of the .011% carbon steel, there is a very small amount of pearlite present, - the main constituent of this steel being free ferrite. The shape of the grains is practically the same in both pictures, though those in the normalized sample are much larger.

The second set of pictures are those of a .15% carbon steel. This is in the class of low carbon steel. An examination will show that there is a marked increase in the amount of pearlite and a decrease in the amount of free ferrite. This is due to the fact that the additional carbon has combined with some of the free ferrite to form Fe_3C , and this combines in turn with more ferrite to form pearlite.



.15% Carbon Steel.
Etched with HNO_3 in
 $\text{C}_2\text{H}_5\text{OH}$.
Mag. 80 x
Sample as received.



.15% Carbon Steel.
Etched with HNO_3 in
 $\text{C}_2\text{H}_5\text{OH}$.
Mag. 80 x
Heated to 1700°F and
cooled in furnace 24
hrs.

Medium High Carbon Steels.

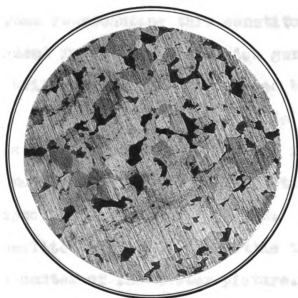
On the next page are shown photomicrographs of steel having a carbon content of .39%. In comparison with the structures of the preceding samples, it will be noticed that the increase in the amount of carbon has again increased the amount of pearlite, correspondingly decreasing the amount of free ferrite.

These three samples have shown that the area of free ferrite has been greater than the area of pearlite. The latter sample contains slightly less than one-half the amount of carbon that eutectoid steel contains, and since eutectoid steel is composed entirely of pearlite, it would be expected that this sample would contain approximately equal amounts of pearlite and free ferrite, with the latter a little in excess. This is clearly shown by the pictures, and in the samples to follow, it will be noticed that the amount of pearlite is greater than the amount of free ferrite.

The next two pictures are of .55% carbon steel. When steel contains but a small, although appreciable, amount of ferrite, as in the case with carbon contents between .50 and .70% the ferrite frequently forms envelopes or membranes surrounding the pearlite grains, an arrangement generally described as a "net-work" structure, pearlite forming the meshes and the free ferrite the net proper. This net-work structure is



.39% Carbon Steel.
Etched with HNO_3 in
 $\text{C}_2\text{H}_5\text{OH}$.
Mag. 80 x
Sample as received.



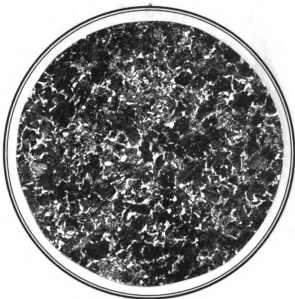
.39% Carbon Steel.
Etched with HNO_3 in
 $\text{C}_2\text{H}_5\text{OH}$.
Mag. 80 x
Heated to 1700°F and
cooled in furnace 24
hrs.

shown very clearly in the accompanying photomicrographs. The polyhedral grains of free ferrite have disappeared due to the great amount of pearlite.

High Carbon Steels.

The steels previously discussed have contained a smaller percentage of carbon than eutectoid steel and are called "hypo-eutectoid" steels. The following discussion deals with "hyper-eutectoid" steels and these contain a larger percentage of carbon than eutectoid steel. We were unable to obtain a sample of eutectoid steel, in which the structure would be entirely pearlite, but the photomicrographs of the .93% carbon steel show a very large amount of it, - the dark areas representing this constituent. The light areas represent free cementite, which generally remains bright and brilliant after being etched by nitric acid.

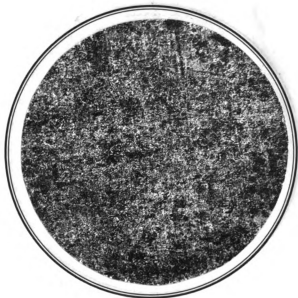
The 1.08% carbon steel is practically the same, with a slightly greater amount of free cementite. It will be noticed that the grain structure does not appear until the specimen has been normalized. A very large grain of pearlite is noticeable a little to the upper left of the center of the latter picture. The lamellae can be plainly seen even at a magnification of only 80x.



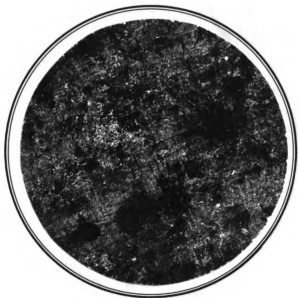
.56% Carbon Steel.
Etched with HNO_3 in
 $\text{C}_2\text{H}_5\text{OH}$.
Mag. 80 x
Sample as received.



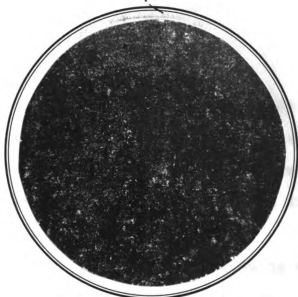
.56% Carbon Steel.
Etched with HNO_3 in
 $\text{C}_2\text{H}_5\text{OH}$.
Mag. 80 x
Heated to 1700°F and
cooled in furnace 24
hrs.



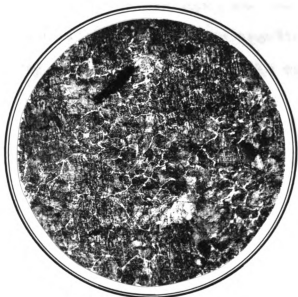
.93% Carbon Steel.
Etched with HNO_3 in
 $\text{C}_2\text{H}_5\text{OH}$.
Mag. 80 x
Sample as received.



.93% Carbon Steel.
Etched with HNO_3 in
 $\text{C}_2\text{H}_5\text{OH}$.
Mag. 80 x
Heated to 1700°F and
cooled in furnace 24
hrs.



1.08% Carbon Steel.
Etched with HNO_3 in
 $\text{C}_2\text{H}_5\text{OH}$.
Mag. 80.x
Sample as received.



1.08% Carbon Steel.
Etched with HNO_3 in
 $\text{C}_2\text{H}_5\text{OH}$.
Mag. 80 x
Heated to 1700°F in
furnace and cooled
24 hrs.

CONCLUSION.

The foregoing analyses have shown that carbon is a very important constituent of steel. The tensile test shows the corresponding increase or decrease in the physical properties with the increase in the carbon content.

In comparing our results with those obtained by other men, we find that they are practically the same. The elastic limits and the maximum strengths for high carbon steels are less than those given in Lioutweiler's "Machine Design", but this is probably due to the heat treatment which we gave our samples. However, the general outline of the curves are practically the same as those shown in Johnson's "Materials of Construction".

DATA.

Sample No.1.

Chemical Analysis:-

Carbon - .011%	Manganese - .017%
Phosphorus - .008%	Sulphur - .032%

Hardness:-

Bar	Before Heat Treating		After H.T.	
	Shore	Brinell	Shore	Brinell
A	18	80.6	16	74.0
B	19	82.0	16	72.7
C	18	80.6	16	72.7
D	18	80.6	16	----
Average	18	81.0	16	73.1

Tensile Test.

Bar.	A	B	C	D
Dia. before pulling	.504	.505	.461	.505
" after "	.274	.274	----	.276
Area before "	.1995	.2003	-----	.2003
" after "	.0590	.0590	-----	.0598
Difference in area	.1405	.1413	----	.1405
% Reduction of area	70.5	70.6	----	70.2
Length after pulling	2.90	2.91	----	2.92
" before "	2.00	2.00	2.00	2.00
Difference in length	0.90	0.91	----	0.92
% Elongation	45.0	45.5	----	46.0
Load @ elastic limit	3000	2850	3100	3100
Stress @ E.L. #/sq."	15000	14300	----	15500

Sample No. 1.(contd)

Bar	A	B	C	D
Maximum load #	8600	8700	----	8650
Max. Stress #/sq."	43000	43500	----	43250
Elastic Ratio	.348	.330	----	.358
Mod. of Elasticity (millions)	18.8	17.9	----	19.4
Elastic Resilience ("#/cu.")	11.9	11.4	----	12.4
Unit deformation (in.)	.0008	.0008	----	.0008
Fracture	Semi Cup and Cone.			
Remarks:-	Bar C was not completely broken.			

Sample No. 2

Chemical Analysis:-

Carbon - .15%	Manganese - .30%
Phosphorus- .010%	Sulphur - .048%

Hardness:-

After Heat Treating

Bar	Shore	Brinell
A	17	----
B	17	----
CC	17	89.3
D	17	89.3
Average	17	89.3

Sample No. 2. (contd)

Tensile Test

Bar	A	B	C	D
Dia. before pulling	.504	.504	.504	.505
" after "	.295	.298	.300	.287
Area before "	.1995	.1995	.1995	.2003
" after "	.0684	.0698	.0707	.0647
Diff. in area	.1311	.1297	.1288	.1356
% Reduction of Area	65.7	65.0	64.5	62.8
Length after pulling	2.82	2.82	2.80	2.82
" before "	2.00	2.00	2.00	2.00
Diff. in length	0.82	0.82	0.80	0.82
% Elongation	41.0	41.0	40.0	41.0
Load @ E.L. #	6000	6500	6400	6000
Stress @ E.L. #/sq."	30100	32600	32100	30000
Maximum load #	10200	10300	10400	10500
Max. Stress #/sq."	51200	51700	52200	52700
Elastic ratio	.580	.630	.616	.570
Mod. of elasticity (millions)	33.0	29.6	26.8	30.0
Elastic Resilience ("#/cu.")	13.6	17.9	18.7	15.0
Unit deformation	.0009	.0011	.0012	.0010
Fracture	Semi cup and cone			
Remarks:-				

1. The first step is to identify the problem or question that needs to be answered.

2. The second step is to gather relevant information and data to address the problem.

3. The third step is to analyze the information and data to identify patterns and trends.

4. The fourth step is to develop a hypothesis or a proposed solution based on the analysis.

5. The fifth step is to test the hypothesis or solution through experiments or observations.

6. The sixth step is to evaluate the results of the tests and determine if the hypothesis is supported.

7. The seventh step is to draw conclusions based on the evaluation of the results.

8. The eighth step is to communicate the findings and conclusions to the relevant audience.

9. The ninth step is to reflect on the process and identify areas for improvement.

10. The tenth step is to apply the knowledge and skills gained from the process to other situations.

11. The eleventh step is to continue to learn and grow from the experience.

12. The twelfth step is to share the knowledge and skills with others to help them learn and grow.

13. The thirteenth step is to stay up-to-date on the latest developments in the field.

14. The fourteenth step is to seek out new challenges and opportunities for growth.

15. The fifteenth step is to maintain a positive attitude and a growth mindset.

16. The sixteenth step is to be open to feedback and criticism.

17. The seventeenth step is to be persistent and not give up easily.

18. The eighteenth step is to be creative and think outside the box.

19. The nineteenth step is to be collaborative and work well with others.

20. The twentieth step is to be resilient and bounce back from setbacks.

21. The twenty-first step is to be curious and ask questions.

22. The twenty-second step is to be organized and manage time effectively.

23. The twenty-third step is to be flexible and adapt to change.

24. The twenty-fourth step is to be proactive and take initiative.

25. The twenty-fifth step is to be a lifelong learner.

Sample No. 3.

Chemical Analysis:-

Carbon - 0.23%	Manganese - .37%
Phosphorus - .008%	Sulphur - .048%

Hardness:-

Bar	Before H.T.		After H.T.	
	Shore	Brinell	Shore	Brinell
A	25	----	19	99.2
B	24	121	18	95.5
C	25	121	20	99.2
D	24	116	18	93.7
Average	24.5	119	19	96.9

Tensile Test

Bar	A	B	C	D
Dia. before pulling	.477	.445	.477	.477
" after "	.290	.266	.262	.270
Area before "	.1787	.1555	.1787	.1787
" after "	.0661	.0556	.0539	.0573
Diference in area	.1126	.0999	.1248	.1214
% Reduction of area	63.0	63.5	70.0	68.0
Length after pulling	2.78	2.78	2.82	2.78
" before "	2.00	2.00	2.00	2.00
Diff. in length	0.78	0.78	0.82	0.78
% Elongation	39.0	39.0	41.0	39.0

Sample No. 3. (contd)

Bar	A	B	C	D
Load at E.L. #	4200	3500	4000	4000
Stress @ E.L. #/sq."	23500	22500	22500	22500
Max. load #	9100	7900	9200	9200
Stress @ max. load #/sq."	51000	50800	51800	51800
Elastic ratio	.500	.444	.435	.435
Mod. of Elasticity (millions)	21.4	22.5	22.5	22.5
Elastic Resilience ("#/cu.")	12.9	11.3	11.3	11.3
Unit deformation	.0011	.0010	.0010	.0010
Fracture	Semi cup and cone			

Sample No. 4.

Chemical Analysis:-

Carbon - .25	Manganese - .58
Phosphorus - .015	Sulphur - .018

Hardness:-

Bar	Before H.T.		After H.T.	
	Shore	Brinell	Shore	Brinell
A	19	123	21	140
B	19	123	21	121
C	20	123	21	143
D	19	123	21	126
Average	19	123	21	133

Sample No 4. (contd)

Tensile Test

Bar	A	B	C	D
Dia. before pulling	.506	.504	.506	.506
" after "	.339	.350	.340	.342
Area before "	.2011	.1995	.2011	.2011
" after "	.0923	.0962	.0908	.0917
Diff. in area	.1088	.1033	.1103	.1094
% Red. of area	53	52	55	54.5
Length after pulling	2.70	2.68	2.68	2.66
" before "	2.00	2.00	2.00	2.00
Diff. in length	0.70	0.68	0.68	0.66
% Elongation	35	34	34	33
Load @ E.L. #	5600	6000	5800	6300
Stress @ E.L. #/sq."	27900	30100	28900	31300
Max Load #	12500	13800	12600	12600
Max. Stress #/sq."	52600	69200	62600	62600
Elastic Ratio	.462	.436	.462	.500
Mod. of Elasticity (millions)	31.0	30.1	32.2	31.3
Elastic Resilience ("#/cu.")	12.6	15.0	13.0	15.7
Unit deformation	.0009	.0010	.0009	.0010
Fracture	Semi cup and cone			

Sample No. 5.

Chemical Analysis:

Carbon - .39%

Manganese - .58%

Phosphorus - .035%

Sulphur - .065%

Hardness:-

Bar	Before H.T.		After H.T.	
	Shore	Brinell	Shore	Brinell
A	21	127	24	159
B	22	131	20	131
C	21	131	24	183
D	22	135	19	137
Average	21.5	131	22	153

Tensile Test

Bar	A	B	C	D
Dia. before pulling	.505	.500	.476	.506
" after "	.416	.414	.394	.417
Area before "	.2005	.1963	.1780	.2011
" after "	.1359	.1346	.1219	.1366
Diff. in area	.0641	.0617	.0561	.0645
% Red. in area	32	31.5	31.5	32
Length before pulling	2.00	2.00	2.00	2.00
" after "	2.50	2.48	2.50	2.48
Diff. in length	0.50	0.48	0.50	0.48
% Elongation	25	24	25	24

Sample No. 5. (contd)

Bar	A	B	C	D
Load @ E.L. #	7500	8000	6500	7300
Stress @ E.L. #/ sq."	37500	40700	36600	36400
Maximum load #	16200	15700	14500	16000
Max. Stress #/sq."	81000	80000	81400	79600
Elastic Ratio	.466	.508	.450	.458
Mod. of Elasticity (millions)	28.9	25.4	36.6	30.3
Elastic Resilience ("#/cu.")	24.3	32.6	18.3	21.9
Unit deformation	.0013	.0016	.0010	.0012
Fracture	Semi cup and cone			

Sample No. 6.

Chemical Analysis:-

Carbon - .56%	Manganese - .38%
Phosphorus - .008%	Sulphur - .025%

Hardness:-

Bar	Before H.T.		After H.T.	
	Shore	Brinell	Shore	Brinell
A	27	170	22	179
B	26	170	23	179
C	26	167	23	179
D	26	170	23	170
Average	26	170	23	179

Sample No.6. (contd)

Tensile Test

Bar	A	B	C	D
Dia. before pulling	.444	.451	.476	.491
" after "	.390	.390	.417	.443
Area before "	.1548	.1598	.1780	.1893
" after "	.1195	.1195	.1366	.1541
Diff. in area	.0353	.0403	.0414	.0352
% Red. of area	23	25	23	19
Length after pulling	2.44	2.42	2.42	2.38
" before "	2.00	2.00	2.00	2.00
Diff. in length	0.44	0.42	0.42	0.38
% Elongation	22	21	21	19
Load @ E.L. #	5000	5000	6000	7000
Stress @ E.L. #/sq."	32300	31300	33700	36900
Maximum load #	13000	13600	15400	16200
Stress @ max. load (#/ sq.)	84000	85000	86600	95500
Elastic Ratio	.385	.369	.389	.432
Mod. of Elasticity (millions)	29.3	28.5	30.6	31.9
Elastic Resilience ("#/cu.")	17.8	17.2	18.6	21.4
Unit deformation	.0011	.0011	.0011	.0012
Fracture	Straight			

Sample No. 7

Chemical Analysis:-

Carbon - .63%

Manganese - .23%

Phosphorus - .008%

Sulphur - .015%

Hardness:-

Bar	Before H.T.		After H.T.	
	Shore	Brinell	Shore	Brinell
A	31	230	27	255
B	31	242	24	217
C	31	235	26	235
D	31	235	24	217
Average	31	235	26	231

Tensile Test

Bar	A	B	C	D
Dia. before pulling	.476	.451	.506	.451
" after "	.447	.428	.475	.427
Area before "	.1706	.1598	.2011	.1598
" after "	.1569	.1439	.1772	.1432
Diff. in area	.0137	.0159	.0239	.0166
% Red. of area	7.8	10	12	10
Length after pulling	2.22	2.20	2.24	2.22
" before "	2.00	2.00	2.00	2.00
Diff. in length	0.22	0.20	0.24	0.22
% Elongation	11	10	12	11

Sample No.7. (contd)

Bar		A	B	C	D
Load @ E.L.	#	7000	6500	7500	6500
Stress @ E.L.	#/sq."	41000	40600	37300	40000
Maximum load	#	20000	18100	22500	18000
Stress @ Max. load	(#/sq.")	117500	133200	112000	122800
Elastic Ratio		.350	.357	.333	.359
Mod. of Elasticity	(millions)	30.4	31.2	32.1	31.6
Elastic Resilience	(in ² /cu. in.)	27.6	26.4	21.7	26.3
Unit deformation		.0013	.0013	.0012	.0013
Fracture		Straight			

Sample No.8

Chemical Analysis:-

Carbon - .94%	Manganese - .27%
Phosphorus - .010%	Sulphur - .012%

Hardness:-

Bar	Before H.T.		After H.T.	
	Shore	Brinell	Shore	Brinell
A	24	174	25	235
B	26	174	27	229
C	24	174	27	235
D	25	183	25	223
Average	25	176	26	231

Sample No. 8. (contd)

Tensile Test

Bar	A	B	C	D
Dia. before pulling	.506	.451	.451.	.476
" after "	.482	----	----	.455
Area before "	.2011	----	----	.1780
" after "	.1825	-----	----	.1626
Diff. in area	.0186	----	----	.0154
% Red. of area	9.3	----	----	8.7
Length after pulling	2.18	----	----	2.18
" before "	2.00	----	----	2.00
Diff. in length	0.18	----	----	0.18
% Elongation	9	----	----	9
Load @ E.L. #	7500	6000	6000	6500
Stress E.L. #/sq."	37300	37500	37500	36500
Maximum Load #	26300	18900	18900	22300
Max. Stress #/sq."	117400	118300	118300	125200
Elastic Ratio	.319	.318	.318	.293
Modulus of Elasticity (millions)	31.0	31.2	31.3	30.4
Elastic Resilience (in ² /cu. in)	22.4	22.6	22.5	21.9
Unit deformation	.0012	.0012	.0012	.0012

Fracture

Straight

Remarks:-

Bars B and C broke outside the punch marks.

Sample No. 9.

Chemical Analysis:-

Carbon - 1.08%

Manganese - .34%

Phosphorus - .025%

Sulphur - .014%

Hardness:-

Bar	Before H.T.		After H.T.	
	Shore	Brinell	Shore	Brinell
A	30	225	28	260
B	34	228	28	264
C	34	234	28	261
D	34	229	28	269
Average	33	229	28	264

Tensile Test

Bar	A	B	C	D
Dia. before Pulling	.505	.505	.505	.504
" after "	.487	----	----	.489
Area before "	.2008	----	----	.1995
" after "	.1863	---	----	.1878
Diff. in area	.0140	----	----	.0117
% Red. of area	7	----	----	6
Length after pulling	2.15	----	----	2 2.15
" before "	2.00	----	----	2.00
Diff. in length	0.15	----	----	0.15
% Elongation	7.5	----	----	7.4

Sample No. 9. (comtd)

Bar	A	B	C	D
Load @ E.L. #	12000	11000	11500	11600
Stress @ E.L. #/sq. in.	60000	55000	57500	55100
Maximum load #	23900	21700	23200	23000
Max. Stress #/sq. in.	119500	108500	116000	105000
Elastic Ratio	.503	.507	.496	.525
Mod. of Elasticity (millions)	32.4	30.5	31.9	29.0
Elastic Resilience ("#/cu. in.)	55.5	40.6	52.6	52.3
Unit deformation	.0019	.0018	.0018	.0019

Fracture

Straight

Remarks:- Bars B and C broke outside punch marks.

Summation of Data for Curves.

Carbon Content	E.L. #/sq.in.	Max.Stress #/sq.in.	Modulus of Elasticity	Elastic Resilience
.011%	14900	43250	18,700,000	11.9
.15	31200	51500	29,900,000	16.3
.23	22800	51400	22,100,000	11.7
.25	29500	64800	31,200,000	14.1
.39	37800	80500	30,500,000	24.3
.56	33500	85300	30,100,000	18.5
.63	39900	113900	31,300,000	25.5
.94	37200	119800	31,000,000	22.3
1.08	56900	112300	30,900,000	52.3

Carbon Content	Red.of Area	Elonga- tion	Hardness		After H.T. Shore	Brinell
			Before H.T. Shore	Brinell		
.011%	70.4%	45.0%	18	81	16	73.1
.15	64.5	48.0	19	86	17	89.3
.23	66.1	39.5	24	123	19	96.9
.25	53.6	34.0	19	123	21	133.0
.39	31.8	24.5	21.5	131	22	153.0
.56	22.5	20.8	26	170	23	179.0
.63	9.95	11.0	31	235	26	231.0
.94	9.0	9.0	26	174	26	231.0
1.08	6.5	7.5	33	229	28	264.0

SAMPLE COMPUTATIONS.

The following set of computations is an example of how foregoing data was obtained. These figures are those of Bar "A" of the .94% carbon.

From the stress-strain diagram, which, was plotted from the readings taken from the testing machine and Berry strain gauge, we took the load at the Elastic Limit and also the unit deformation. The latter is found by reading the abscissa of the E.L. and dividing it by 2, since the distance between the punch marks on the test bar was 2 inches.

Load at E.L. - 7500#

Maximum load - 23600#

Unit deformation - .0012"

Diameter before pulling - .506"

" after " - .482"

Area before " - .2011 sq.in.

" after " - .1825 "

Difference in area - .0186 "

% Reduction in area = $\frac{.0186}{.2011} = 9.3\%$

Length after pulling - ~~2.18~~ 2.18"

" before " - 2.00"

Difference in length - 0.18"

% Elongation = $\frac{0.18}{2} = 9.0\%$

Stress at Elastic Limit = $\frac{7500}{.2011} = 37300 \text{ \#/sq.in.}$

Maximum stress = $\frac{23600}{.2011} = 117400 \text{ \#/sq.in.}$

Sample Computations (contd)

$$\text{Elastic Ratio} = \frac{\text{stress @ E.L.}}{\text{max. stress}} = \frac{37300}{117400} = .319$$

$$\begin{aligned}\text{Modulus of Elasticity} &= \frac{\text{unit stress}}{\text{unit deformation}} \\ &= \frac{37300}{.0012} \\ &= 31,000,000\end{aligned}$$

$$\begin{aligned}\text{Elastic Resilience} &= \frac{(\text{unit stress})^2}{2 \times \text{Mod. of Elasticity}} \\ &= \frac{(37300)^2}{2 \times 31,000,000} \\ &= 22.4 \text{ \#}/\text{cu.in.}\end{aligned}$$



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