HARDENABILITY TEST OF GRAY CAST IRON
BY JOMINY END-QUENCH METHOD

By Chin Liu

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Introduction

Hardenability, which may be defined as the capacity of a ferrous material to harden when cooled from the austenitic range, is generally evaluated from the hardness produced by different cooling rates in a given piece. In a more inclusive sense the hardenability may also be considered as the relationship between rates of cooling from above the austenitic range and the hardness and microstructures developed as a result. Because this property of hardenability has assumed increasing importance during the past several years, a number of so-called hardenability tests have been developed to measure it.

Inasmuch as the hardenability testing of steels is well known, the information obtained from such a test has been an important guide for the selection of materials for certain purposes. However, very few investigators have done any work on this sort of test for gray cast iron, which, because of its high damping capacity, low melting point, cheapness, and so forth, has been made and used for centuries as an important engineering material. Gray cast iron is an alloy of iron and carbon just as a steel is, can be alloyed with alloying elements to improve certain properties, and can also be heat-treated to obtain certain structures, to change the hardness, to reduce the internal stress, and the like as a steel can be; but the results obtained from some of the processes mentioned here may be different to some extent from those obtained from a steel, because a gray cast iron usually contains higher percentages of both silicon and carbon, which cause graphitization much more easily in cast iron than in a steel.

The major purpose of this research was to determine the hardenability of gray cast iron, and to offer some information to the user about the hardenability property of this kind of material. As we know, the hardenability of a ferrous material can be affected by the composition, the austenitic grain size, or the quenching temperature of the material; and the change in any one of these factors would have different results. For instance, such elements as nickel, silicon, manganese, chromium, molybdenum, vanadium, and boron, when present in steel would increase the hardenability; whereas such elements as aluminum, and cobalt, when present in steel would reduce the hardenability. However, although this has to determined by actual experiments. As for the effects of grain size, usually the coarse-grained materials have higher hardenability than fine-grained materials, because the fine-grained materials have more grain boundaries, and are more reactive and easily changed to pearlite.

The research was divided into the following parts:

(1). Heating And Quenching: In order to study the effects of different soaking time with same quenching temperature, and same soaking time with different quenching temperatures, two sets of standard Jominy bars were used, and treated by the Jominy End-Quench Process.

(2). Hardness Measurements: Rockwell C hardness readings were measured along the flat surfaces of all these bars, after they were treated as mentioned above.

(3). Combined Carbon Analyses: After the hardness readings were measured, samples were taken from some of these bars, and analyzed for graphitic carbon content. The combined carbon content for each specimen was then obtained by the difference of total carbon and graphitic carbon content.

(4). Examination of Microstructures: Besides the combined carbon analyses, the bars were also polished, etched with 5 percent picral, and examined under microscope after the treatments mentioned above.

From these experiments, it is interesting to note that the martensitic structure is present all the way through, along the whole length on all bars, when they were ground, polished, etched, and examined under microscope, whereas the hardness measurements, as well as the combined carbon contents show different results on different bars.

Testing Method And Equipment Used

Several methods are available for the hardenability testing of ferrous materials. According to the fields for which they are used, these methods can be classified as: (1). for deep-hardening materials, (2). for shallow-hardening materials, (3). for medium-hardening materials. The method adopted for the present experiment, called "Standard Jominy End-Quench Test", is the one usually adopted for medium-hardening or common alloy steels.

Preparation of the Test Bar

For the Standard Jominy End-Quench Test, a special bar should be used. The bar is a cylinder 1 inch in diameter, and 4 inches long, on one end of which is a machined shoulder, 1/8 inch in thickness and 1 1/4 inches in diameter to permit the bar to be suspended vertically in the quenching fixture. (as shown in Fig. 1).

Quenching Fixture

After the bar has been heated to the desired temperature above the critical range, it is quenched in a specially designed quenching fixture. The fixture is constructed so that the bar is held 1/2 inch above the water opening, in order that a column of water may be directed against the bottom of the

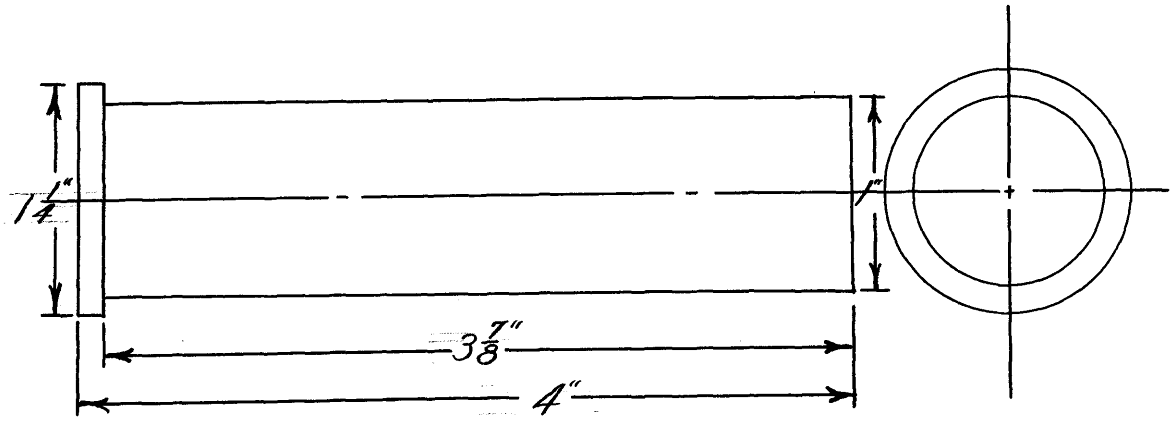

Fig. 1 --- Standard Jominy Bar.

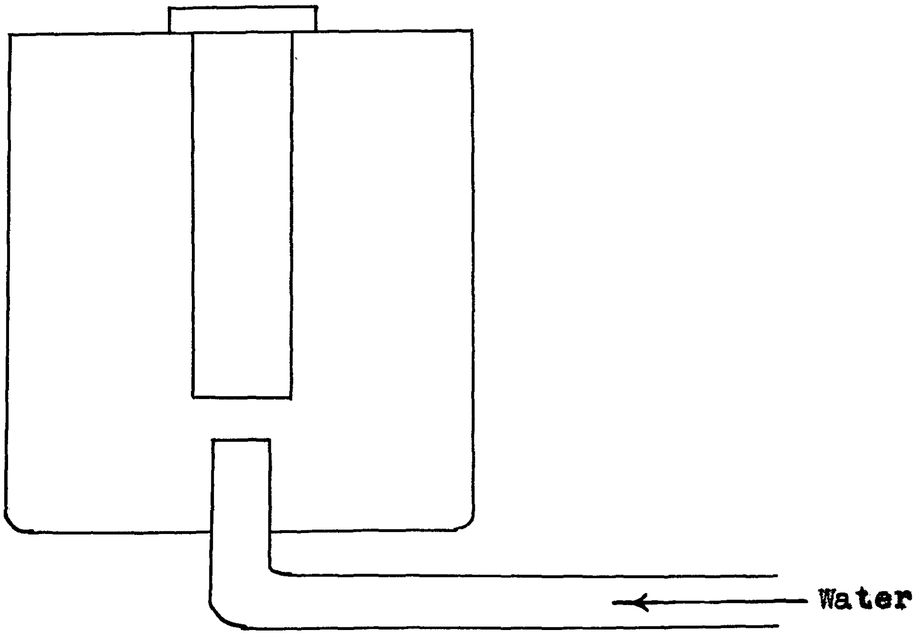

Fig. 2 --- Quenching Fixture.

bar. The water opening is 1/2 inch in diameter, and adjustment is made so that before the bar is placed over it, a column of water 2 1/2 inches high comes from the opening (Fig. 2). The water temperature is kept at 75 F., plus or minus 5 F., and a condition of still air is maintained around the bar during cooling. The time spent in transferring the bar from the heating furnace to the quenching fixture should not be more than five seconds; otherwise, the temperature of the bar would drop below the temperature desired.

Measurements of Hardness

After the bar has been heated, and quenched, two parallel flat surfaces, 180 degrees apart and o.015 inch deep, are ground along the entire length of the bar. Care must be taken to avoid tempering when the parallel flat surfaces are ground. After grinding, it is good practice to etch the ground surfaces with 5 percent picral or other suitable etchant, to determine whether grinding has caused any tempering. The hardness is then determined along the ground and polished surface at intervals of 1/16 inch from the water-cooled end for the first inch, 1/8 inch for the second inch, and 1/4 inch for the remainder of the bar. The hardness readings are averaged at the identical distances from the quenched end on the two parallel surfaces.

Hardenability Curve

The hardness measurements from the flat surface are usually plotted against the distances from the quenched end of the bar treated. The curves obtained afford a means for readily distinguishing between the relative hardenability of similarly heat-treated materials.

The hardenability specification is usually expressed by J50 = 7, J55 = 6, and so forth, in which 50 and 55 represent the Rockwell C hardnesses measured from a distance of 7/16 inch and 6/16 inch from the quenched ends respectively.

Experimental Work And Results

The major object of the present experiment was to investigate the hardenability of a gray cast iron. At the start, the work was concentrated to the investigation of hardenability data; however, besides hardenability data, another interesting phenomenon was found; that is, the hardness changes in specimens with the changes in quenching temperatures and in holding time for heating. In order to interpret these results, analyses of combined carbon content in some of these bars were made, after the bars had been treated.

Sample Used

History And Composition: The sample used for the present experiment was obtained from Meehanite Metal Corporation, Cleveland, Heights, Ohio, and was in the cast condition and of the following composition:

T. C.	Si	Mn	P	S	Cu	Mo	Cr
2.87	1.41	0.85	0.13	0.075	1.86	0.72	0.12

Meehanite is a trade name used for the gray cast iron in which calcium silicide has been used for the refinement and better distribution of graphite.

Preparation of the Standard Jominy Bars: The Standard Jominy bars were machined from the sample mentioned above. Fifteen bars were used for the subsequent experiments, which will be described later.

Heating And Quenching

The bars were heated in a small electrically heated furnace, and quenched in the specially designed quenching fixture mentioned before. The temperature was controlled by an alumel-chromel thermocouple. By changing the resistance on the furnace, the temperature was controlled to within plus or minus 5° F., the temperature desired. The specimen covered with cast iron shavings of the same composition as the specimen itself was placed in the center of the furnace, as soon as the power was turned on. The shavings covering the specimen were used for preventing decarburization of the specimen. The specimen was heated very slowly, about eight degrees per minute. As soon as the specimen reached the desired temperature, timing was started.

Measurements of Hardness

After the specimen had been quenched, it was then ground to a depth of 0.015 inch along the two surfaces 180 degrees apart. When being ground, the specimen was kept sufficiently cool with water to avoid tempering of the specimen. The depth of the ground part was measured by a micrometer, and care was taken to get the same depth on all bars. The ground surface was then polished, etched with 5 percent picral, and examined under microscope to see if the specimen had ever been tempered. Finally the Rockwell C hardness readings were taken along the flat surfaces in the way mentioned before, and then averaged at the identical distances from the quenched end on the two parallel flats. These averaged figures were then plotted against the distances from the quenched end.

Combined Carbon Analyses

The combined carbon content was obtained by the difference of total carbon and graphitic carbon. The graphitic carbon analyses may be divided into two steps:

(1). Separation of graphitic carbon from combined carbon in the sample: This was done by the use of nitric acid (sp. gr. 1.2), in which the graphitic carbon in insoluble and can therefore be separated by filtering.

(2). Ignition of the carbon: The residue from the filter was then dried, and placed in a porcelain boat in which a small amount of alumina was mixed. The boat was placed in the hot zone of a tube furnace in which a temperature of 950° C. was maintained. During igniting, a rapid current of oxygen was passed into the tube for twelve mintes. At the end of twelve minutes, the bulb containing soda asbestos was removed and weighed. The gain in weight of this bulb was due to the carbon dioxide absorbed, the amount of which can be calculated as the percentage of carbon in the sample.

Experimental Work Done

Study of Inluence of Quenching Temperatures: In order to determine the influence of quenching temperatures on hardenability of the material used, nine standard Jominy bars of the composition mentioned above were heated to 1400°, 1450°, 1500°, 1550°, 1600°, 1700°, 1750°, 1800° and 1950° F. respectively for one hour, next quenched in the quenching fixture. The hardness readings were then taken along the flat surfaces, averaged, and plotted against the distances from the quenched end. The results obtained are summarized in Table 1.

Study of Influence of Soaking Time: Three temperatures, 1400°, 1700° and 1950° F. were chosen for this experiment. Six standaed Jominy bars of the composition mentioned above were used; three of them were heated to these temperatures for two hours, and another three were heated to the same temperature but for three hours, and all were quenched in the same way mentioned above. The hardness readings were taken along the flat surfaces, averaged, and then plotted against the distances from the quenched end. The results obtained are summarized in Table 2.

Changes in Combined Carbon Content: Graphitic carbon content determinations were run on specimens which were heated to 1400°, 1700°, and 1950° F. for one, two, and three hours, and the total carbon content was also checked by the combustion method. The combined carbon content was obtained by the difference of total carbon and the graphitic carbon content. The results obtained are summarized in Table 3.

Examination of Microstructures: After the different treatments mentioned above, the bars were ground, polished, etched with 5 percent picral, and then examined under microscope. The results obtained may be described as follows:

1. For low heating temperatures with one hour soaking time: The microstructure shown in Fig. 9 represents the microstructures of the bars, which were heated to 1400°, 1450° F. and so on, for one hour. The constituents present are martensite, cementite, graphite, and some steadite.

2. For high heating temperature with one hour soaking time: The microstructure shown in Fig. 10 represents the microstructures of the bars, which were heated to 1950°, 1800° F. and so on, for one hour. The constituents present are martensite, cementite, graphite, and some steadite.

3. For low heating temperature with two or three hours soaking time: The microstructure shown in Fig. 11 represents the microstructures of the bars, which were heated to 1400°, 1450° F. and so on, for two or three hours. The constituents present are martensite, cementite, graphite,

and some steadite.

4. For high heating temperature with two or three hours soaking time: The microstructure shown in Fig. 12 represents the microstructures of the bars, which were heated to 1950°, 1800° F. and so on, for two or three hours. The constituents present are martnesite, cementite, graphite, and some steadite.

Discussions of the Results

The hardness measurements, from which the hardenability curves were plotted, and the carbon analyses of the specimens give some interesting results: not only the high hardenability, but also the changes in hardness due to different quenching temperatures and soaking time.

Hardenability

For steel, hardenability is affected by several factors: if either the composition or the austenitic grain size is changed, the hardenability of the material will be changed to some extent. However, the austenitic grain size is determined by the quenching temperature, and soaking time, because higher quenching temperature and longer soaking time would cause the grain growth of the material.

From the analyses of the specimen given on page 9, it can be seen that such elements as Si (1.41%), Mn (0.85%), and Cr (0.12%), which commonly dissolve in austenite prior to quenching, and increase the hardenability to a greater extent are very high in percentage. In steel, they increase the hardenability by shifting the S curve to the right so that the decomposition of austenite is delayed. However, in gray cast iron these elements might have the same effects on the S curve, although the actual data have to be worked out by experiments. Copper when present in steel favors deep hardening; its relative effect is much greater in the high-carbon than in low-carbon steels. Therefore, when copper is present in cast iron, the deep-hardening effect must be much more pronounced, because cast iron contains much more carbon than steel, and carbon increases the deep-hardening effect of copper.

From the above discussions, it may be concluded that the hardenability of this material should be high. Actually, from the hardness measured, curves plotted, and the microstructures obtained (Figs. 9, 10, 11, 12), it can be seen that the hardenability of this material is high. All the specimens were ground, polished, etched with 5 percent picral, and then examined under microscope; the structures show martensite all the way through along the whole length on all bars, after the bars were heated and quenched. Fig. 9 shows the microstructure of the specimen which was heated to 1400° F. for one hour and was taken from a place about one-half inch from the air-cooled end. Fig. 10 shows the microstructure of the specimen which was heated to 1950° F. for one hour and was taken from a place about one-half inch from the air-cooled end. Fig. 11 shows the microstructure of the specimen which was heated to 1400° F. for three hours and was taken from a place about one-half inch from the air-cooled end. Fig. 12 shows the microstructure of the specimen which was heated to 1950° F. for three hours and was taken from a place about one-half inch from the air-cooled end.

Changes in Hardness

Before discussing the changes in hardness, the following assumptions should be made:

1. Fine graphite particles are more easily dissolved in austenite than large grains of cementite. From Fig. 14, we can see the graphite flakes are rather fine and widely distributed. Moreover, from the heating process mentioned above, the heating rate of the specimens was very slow, about eight degrees per minute; therefore, the cementite has spheroidized to a great extent. This spheroidization made the cementite in the specimen to globularize and not to be changed with ease.

2. High temperatures should cause the decomposition of cementite, but the change in soaking time from one to two or three hours did not cause further deconposition of cementite. for example, when the specimen was heated from 1400° F. to 1950° F., the decomposition of cementite had occurred to some extent, while not any appreciable amount of decomposition of cementite had occurred when the soaking time was increased from one to three hours.

Changes Due to Quenching Temperatures: From Fig. 3 and Table 3, it can be seen that with soaking time of one hour, the higher the quenching temperature, the lower the hardness, as well as the lower the combined carbon content, According to the accepted iron-carbon diagram, when a specimen is heated to just above the A_{c1}, about 0.8% carbon will be dissolved in the austneite, and when the temperature is increased, more carbon will be dissolved. Moreover, according to some investigators' experiments, when both cementite and graphite are present in the same specimen, cementite will be dissolved prior to graphite. When these specimens are quenched, the one which is heated to a higher temperature with more carbon dissolved in the austenite should have higher carbon retained in the resulting martensite than the one which is heated to a lower temperature with less carbon dissolved in the austenite. Therefore, the former has higher hardness readings than the latter. However, for the present experiment, because of the presence of fine graphite particles in the specimen and the formation of spheroidized cementite during the slow heating process used, most of the carbon dissolved might be from graphite, when the specimen was heated to a lower temperature, say, 1400° F., thus large amount of spheroidized cementite was left in the specimen and made the hardness readings higher. While in the specimen, which was heated to a higher temperature, say, 1950° F. for one hour, some of this spheroidized cementite formed at the earlier stage would decompose to some extent, thus making the hardness readings lower (Fig. 10).

Changes Due to Soaking Time: From Figs. 5 and 6 and Table 3, it can be seen that with high constant temperature, the longer the soaking time, the higher the hardness, as well as the higher the combined carbon content. However, when the soaking time was long enough, say, two hours or longer, the hardness, as well as the combined carbon content reached to constant (Fig. 8), but this is not true for the specimen which was heated to a lower temperature, say, 1400° F. For this specimen different soaking time gave the same results (Fig. 4), because the temperature was not high, and the soaking time was not long enough to cause the decomposition of cementite in the original specimen.

When the temperature was increased to, say, 1800° or 1950° F. for two or three hours, the time still was not long, but the temperature was high enough to cause the decomposition of cementite, and the amount decomposed may be nearly the same as that decomposed in the specimen which was heated to the same tmeperature but held for only one hour. However, when the soaking time was longer, more carbon should have been dissolved in the austenite, and retained in the martensite, when quenched, thus making the resulting hardness higher, though this is not true for the specimen which was heated to 1400° F. for one, two and three hours; because the temperature was too close to A_{c1}, even longer soaking time, say, two or three hours, could not cause more carbon to dissolve in the austenite.

Table 1 --- Influence of Quenching Temperature on Hardneability

Specimen No.	Quenching Temp. (°F.)	Soaking Time (Hrs.)	Hardness Readings	Curves
1	1400	1	Table 4	Fig. 3
2	1450	1	" 5	" 3
3	1500	1	" 6	" 3
4	1550	1	" 7	" 3
5	1600	1	" 8	" 3
6	1700	1	" 9	" 3
7	1750	1	" 10	" 3
8	1800	1	" 11	" 3
9	1950	1	" 12	" 3

Table 2 --- Influence of Soaking Time on Hardneability

Specimen No.	Quenching Temp. (° F.)	Soaking Time (Hrs.)	Hardness Readings	Curves
10	1400	2	Table 13	Fig. 4
11	1400	3	" 14	" 4
12	1700	2	" 15	" 5
13	1700	3	" 16	" 5
14	1950	2	" 17	" 6
15	1950	3	" 18	" 6

Table 3 --- Carbon Analyses

Specimen No.	Quenching Temp. (°F.)	Soaking Time (Hrs.)	T. C. (%)	C. C. (%)	G. C. (%)
1	1400	1	2.88	0.91	1.96
10	1400	2	2.87	0.92	1.95
11	1400	3	2.87	0.93	1.94
5	1700	1	2.88	0.80	2.08
12	1700	2	2.87	0.92	1.97
13	1700	3	2.87	0.92	1.95
9	1950	1	2.87	0.73	2.14
14	1950	2	2.88	0.90	1.98
15	1950	3	2.87	0.92	1.95
Sample as cast			2.87	0.62	2.25

Table 4 --- Specimen heated to 1400°F. for one hour.

Distances from quenched end, in.	Hardness readings, Rockwell C On one side	 On the other side	 Ave.
1/16	46.4	45.6	46.0
2/16	56.0	57.0	56.5
3/16	56.0	56.0	56.0
4/16	56.5	57.5	57.0
5/16	56.0	57.0	57.5
6/16	57.0	56.0	56.5
7/16	55.5	56.5	56.0
8/16	56.0	56.0	56.0
9/16	56.5	55.5	56.0
10/16	56.0	56.0	56.0
11/16	56.0	55.0	55.5
12/16	55.0	55.0	55.0
13/16	54.0	56.0	55.0
14/16	55.0	55.0	55.0
15/16	53.0	57.0	55.0
16/16	55.0	55.0	55.0
18/16	54.0	55.0	54.5
20/16	55.0	53.0	54.0
22/16	54.0	53.0	53.5
24/16	52.0	54.4	53.2
26/16	52.0	54.6	53.3
28/16	52.0	54.0	53.0
30/16	53.0	53.0	53.0
32/16	54.0	52.0	53.0
36/16	52.0	53.2	52.6
40/16	51.6	51.6	51.6
44/16	50.0	52.0	51.0
48/16	50.0	51.0	50.5
52/16	50.3	50.3	50.3
56/16	49.0	51.0	50.0
60/16	50.0	50.0	50.0

Specimen as cast: Rockwell C 35.

Table 5 --- Specimen heated to 1450° F. for one hour.

Distances from quenched end, in.	Hardness readings, Rockwell C		
	On one side	On the other side	Ave.
1/16	40.0	40.0	40.0
2/16	48.0	48.0	48.0
3/16	52.0	48.0	50.0
4/16	54.0	50.0	52.0
5/16	56.0	50.0	53.0
6/16	56.0	52.0	54.0
7/16	55.0	54.0	54.5
8/16	55.0	55.0	55.0
9/16	54.6	54.6	54.6
10/16	56.0	55.4	54.8
11/16	54.0	55.2	54.6
12/16	55.4	54.2	54.8
13/16	55.2	54.2	54.7
14/16	55.0	54.0	54.5
15/16	54.4	54.0	54.2
16/16	55.0	53.0	54.0
18/16	53.0	55.0	54.0
20/16	54.0	53.0	53.5
22/16	52.0	54.0	53.0
24/16	54.0	52.0	53.0
26/16	52.8	52.8	52.8
28/16	53.0	52.0	52.5
30/16	54.0	50.0	52.0
32/16	52.0	51.6	51.8
36/16	54.0	48.0	51.0
40/16	50.9	50.7	50.8
44/16	50.0	50.0	50.0
48/16	49.5	49.5	49.5
52/16	49.2	49.2	49.2
56/16	49.0	49.0	49.0
60/16	49.0	49.0	49.0

Table 6 --- Specimen heated to 1500° F. for one hour.

Distances from quenched end, in.	Hardness readings, Rockwell C		
	On one side	On the other side	Ave.
1/16	45.0	45.0	45.0
2/16	50.0	49.0	49.5
3/16	52.0	51.0	51.5
4/16	52.8	52.8	52.8
5/16	54.0	52.0	53.0
6/16	53.0	53.0	53.0
7/16	54.0	52.0	53.0
8/16	53.0	52.6	52.8
9/16	52.6	53.0	52.8
10/16	53.0	53.0	53.0
11/16	54.0	52.0	53.0
12/16	55.0	51.0	53.0
13/16	52.0	54.0	53.0
14/16	53.0	53.0	53.0
15/16	53.0	53.0	53.0
16/16	52.8	52.8	52.8
18/16	53.0	53.0	53.0
20/16	54.0	52.0	53.0
22/16	55.0	51.0	53.0
24/16	54.0	52.0	53.0
26/16	54.0	50.0	52.0
28/16	51.0	51.6	51.3
30/16	50.8	50.8	50.8
32/16	50.0	50.0	50.0
36/16	49.0	51.0	50.0
40/16	49.0	49.0	49.0
44/16	48.0	49.6	48.8
48/16	48.6	48.6	48.6
52/16	58.0	39.0	48.5
56/16	48.2	48.2	48.2
60/16	48.2	48.4	48.3

Table 7 --- Specimen heated to 1550° F. for one hour.

Distances from quenched end, in.	Hardness readings, Rockwell C		
	On one side	On the other side	Ave.
1/16	40.0	41.0	40.5
2/16	46.5	46.5	46.5
3/16	50.0	50.0	50.0
4/16	54.0	53.0	53.5
5/16	54.0	52.0	53.0
6/16	52.8	52.8	52.8
7/16	53.0	52.0	52.5
8/16	54.0	50.0	52.0
9/16	51.0	53.0	52.0
10/16	52.0	52.0	52.0
11/16	54.0	50.0	52.0
12/16	52.0	52.0	52.0
13/16	51.8	51.8	51.8
14/16	51.5	51.5	51.5
15/16	51.3	51.3	51.3
16/16	51.3	51.3	51.3
18/16	51.2	51.2	51.2
20/16	50.5	51.0	50.8
22/16	50.6	50.0	50.3
24/16	50.0	50.4	50.2
26/16	51.0	49.0	50.0
28/16	49.6	49.6	49.6
30/16	49.6	49.0	49.3
32/16	49.0	49.0	49.0
36/16	49.0	48.0	48.5
40/16	48.0	48.0	48.0
44/14	48.0	49.0	48.5
48/16	47.0	48.0	47.5
52/16	48.0	47.0	47.5
56/16	47.5	47.5	47.5
60/16	48.0	47.0	47.5

Table 8 --- Specimen heated to 1600° F. for one hour.

Distances from quenched end, in.	Hardness readings, Rockwell C		
	On one side	On the other side	Ave.
1/16	48.0	48.0	48.0
2/16	56.0	52.0	54.0
3/16	54.4	54.0	54.2
4/16	54.6	54.0	54.3
5/16	54.0	54.0	54.0
6/16	58.0	50.0	54.0
7/16	53.8	53.8	53.8
8/16	54.0	53.0	53.5
9/16	56.0	50.0	53.0
10/16	52.8	52.8	52.8
11/16	52.5	52.5	52.5
12/16	52.2	52.0	52.1
13/16	52.0	51.0	51.5
14/16	52.0	50.0	51.0
15/16	50.8	50.8	50.8
16/16	50.6	50.0	50.3
18/16	50.0	50.0	50.0
20/16	50.0	49.0	49.5
22/16	49.4	49.0	49.2
24/16	49.0	49.0	49.0
26/16	48.8	48.8	48.8
28/16	48.5	48.5	48.5
30/16	48.4	48.0	48.2
32/16	48.7	48.7	48.7
36/16	47.0	47.0	47.0
40/16	48.0	46.0	47.0
44/16	47.0	47.0	47.0
48/16	48.0	46.0	47.0
52/16	45.0	49.0	47.0
56/16	48.0	46.0	47.0
60/16	45.0	49.0	47.0

Table 9 --- Specimen heated to 1700° F. for one hour.

Distances from quenched end, in.	Hardness readings, Rockwell C		
	On one side	On the other side	Ave.
1/16	39.5	39.5	39.5
2/16	44.5	46.0	45.0
3/16	49.0	47.0	48.0
4/16	51.0	49.0	50.0
5/16	50.0	52.0	51.0
6/16	51.0	51.0	51.0
7/16	50.0	50.0	50.0
8/16	51.0	51.0	51.0
9/16	51.0	50.0	50.5
10/16	51.0	50.0	50.5
11/16	52.0	50.0	51.0
12/16	51.0	50.0	50.5
13/16	51.0	51.0	51.0
14/16	51.0	50.0	50.5
15/16	49.0	51.0	50.0
16/16	49.0	49.0	49.0
18/16	50.0	48.0	49.0
20/16	49.0	47.0	48.0
22/16	49.0	48.0	48.5
24/16	48.0	49.0	48.5
26/16	48.0	48.0	48.0
28/16	49.0	49.0	49.0
30/16	46.0	48.0	47.0
32/16	47.0	47.0	47.0
36/16	47.0	47.0	47.0
40/16	45.0	47.0	46.0
44/16	47.0	45.0	46.0
48/16	46.0	48.0	47.0
52/16	46.5	46.5	46.5
56/16	47.0	46.0	46.5
60/16	45.0	49.0	47.0

Table 10 --- Specimen heated to 1750° F. for one hour.

Distances from quenched end, in.	Hardness readings, Rockwell C		
	On one side	On the other side	Ave.
1/16	40.0	40.0	40.0
2/16	46.0	40.0	43.0
3/16	46.0	45.0	45.5
4/16	48.0	46.0	47.0
5/16	49.0	47.0	48.0
6/16	48.6	48.0	48.3
7/16	48.6	48.6	48.6
8/16	48.8	48.8	48.8
9/16	48.0	49.0	48.5
10/16	49.0	49.0	49.0
11/16	50.0	48.0	49.0
12/16	48.8	48.8	48.8
13/16	49.0	48.0	48.5
14/16	48.6	48.0	48.3
15/16	48.6	48.0	48.3
16/16	49.0	47.0	48.0
18/16	48.0	48.0	48.0
20/16	48.0	47.0	47.5
22/16	48.0	46.0	47.0
24/16	49.0	45.0	47.0
26/16	48.0	46.0	47.0
28/16	46.8	46.8	46.8
30/16	47.0	46.0	46.5
32/16	47.0	46.0	46.5
36/16	48.0	44.0	46.0
40/16	47.0	43.0	45.0
44/16	44.8	44.8	44.8
48/16	44.5	44.5	44.5
52/16	46.5	42.5	44.5
56/16	45.0	44.5	44.5
60/16	45.2	45.2	45.2

Table 11 --- Speciemn heated to 1800° F. for one hour.

Distances from quenched end, in.	Hardness readings, Rockwell C		
	On one side	On the other side	Ave.
1/16	40.0	40.0	40.0
2/16	44.0	40.0	42.0
3/16	43.5	43.5	43.5
4/16	46.0	44.0	45.0
5/16	45.8	45.8	45.8
6/16	46.4	46.0	46.2
7/16	46.5	46.5	46.5
8/16	48.0	46.0	47.0
9/16	47.5	47.5	47.5
10/16	48.0	47.0	47.5
11/16	47.0	48.0	47.5
12/16	47.4	47.0	47.2
13/16	49.0	45.0	47.0
14/16	48.0	46.0	47.0
15/16	45.0	49.0	47.0
16/16	46.0	47.0	46.5
18/16	48.0	45.0	46.5
20/16	45.0	48.0	46.5
22/16	46.0	47.0	46.5
24/16	43.0	50.0	46.5
26/16	48.0	44.0	46.0
28/16	47.0	46.0	46.5
30/16	45.8	45.8	45.8
32/16	46.0	45.0	45.5
36/16	46.0	44.0	45.0
40/16	44.5	44.5	44.5
44/16	44.0	44.0	44.0
48/16	46.0	40.0	43.0
52/16	46.0	40.0	43.0
56/16	44.0	42.0	43.0
60/16	43.5	43.5	43.5

Table 12 --- Specimen heated to 1950°F. for one hour.

Distances from quenched end, in.	Hardness readings, Rockwell C		
	On one side	On the other side	Ave.
1/16	39.0	39.0	39.0
2/16	41.0	39.0	40.0
3/16	40.0	42.0	41.0
4/16	44.0	40.0	42.0
5/16	44.0	42.0	43.0
6/16	42.5	44.5	43.5
7/16	44.0	46.0	45.0
8/16	46.5	47.5	47.5
9/16	46.5	46.5	46.5
10/16	46.0	44.0	45.0
11/16	43.0	47.0	45.0
12/16	45.0	45.0	45.0
13/16	45.0	46.0	45.5
14/16	44.0	47.0	45.5
15/16	45.6	45.0	45.3
16/16	45.6	45.0	45.3
18/16	44.0	46.0	45.0
20/16	45.5	45.5	45.5
22/16	46.0	42.0	44.0
24/16	47.0	41.0	44.0
26/16	44.5	44.4	44.5
28/16	46.0	40.0	43.0
30/16	44.0	40.0	42.0
32/16	40.5	41.5	41.0
36/16	41.5	41.5	41.5
40/16	43.0	41.0	42.0
44/16	42.0	40.0	41.0
48/16	40.5	41.5	41.0
52/16	41.0	42.0	41.5
56/16	42.0	42.0	42.0
60/16	40.5	41.5	42.0

Table 13 --- Specimen heated to 1400° F. for two hours.

Distances from quenched end, in.	Hardness readings, Rockwell C		
	On one side	On the other side	Ave.
1/16	46.0	48.0	47.0
2/16	50.0	48.0	59.0
3/16	54.0	56.0	55.0
4/16	55.0	57.0	56.0
5/16	57.0	58.0	57.5
6/16	57.0	57.0	57.0
7/16	55.5	55.5	55.5
8/16	55.0	57.0	56.0
9/16	56.0	56.0	56.0
10/16	54.0	56.0	55.0
11/16	55.5	54.5	55.0
12/16	54.0	54.0	54.0
13/16	55.0	53.0	54.0
14/16	56.0	56.0	56.0
15/16	54.0	54.0	54.0
16/16	52.0	56.0	54.0
18/16	53.5	52.5	53.0
20/16	55.0	51.0	53.0
22/16	54.0	54.0	54.0
24/16	53.0	53.0	53.0
26/16	51.0	53.0	52.0
28/16	52.0	52.0	52.0
30/16	53.0	53.0	53.0
32/16	55.0	51.0	53.0
36/16	52.0	52.0	52.0
40/16	51.0	53.0	52.0
44/16	51.8	51.8	51.8
48/16	50.0	52.0	51.0
52/16	50.0	52.0	51.0
56/16	54.0	49.0	51.5
60/16	50.0	52.0	51.0

Table 14 --- Specimen heated to 1400°F. for three hours.

Distances from quenched end, in.	Hardness readings, Rockwell C On one side	 On the other side	 Ave.
1/16	54.0	56.0	55.0
2/16	52.0	54.0	53.0
3/16	53.0	55.0	54.0
4/16	55.0	55.0	55.0
5/16	56.5	55.5	56.0
6/16	55.5	54.5	55.0
7/16	58.0	56.0	57.0
8/16	53.5	57.5	55.0
9/16	55.5	58.5	57.0
10/16	55.0	55.0	55.0
11/16	56.0	56.0	56.0
12/16	54.0	56.0	55.0
13/16	52.0	54.0	53.0
14/16	54.0	54.0	54.0
15/16	55.0	51.0	53.0
16/16	55.5	54.5	55.0
18/16	53.5	56.5	55.0
20/16	55.0	55.0	55.0
22/16	52.0	54.0	53.0
24/16	54.0	54.0	54.0
26/16	55.5	52.5	54.0
28/16	52.0	52.0	52.0
30/16	51.0	51.0	51.0
32/16	50.0	52.0	51.0
36/16	52.8	52.8	52.8
40/16	50.0	51.0	50.5
44/16	50.0	50.0	50.0
48/16	52.0	52.0	52.0
52/16	50.0	54.0	52.0
56/16	51.0	51.0	51.0
60/16	54.0	50.0	52.0

Table 15 --- Specimen heated to 1700° F. for two hours.

Distances from quenched end, in.	Hardness readings, Rockwell C		
	On one side	On the other side	Ave.
1/16	48.0	47.0	47.5
2/16	55.0	54.0	54.5
3/16	56.0	56.0	56.0
4/16	55.0	55.0	55.0
5/16	54.0	56.0	55.0
6/16	55.0	57.0	56.0
7/16	55.0	53.0	54.0
8/16	52.5	55.5	54.0
9/16	55.5	55.5	55.5
10/16	54.0	54.0	54.0
11/16	56.0	54.0	55.0
12/16	52.0	56.0	54.0
13/16	54.0	54.0	54.0
14/16	54.5	54.5	54.5
15/16	54.0	54.0	54.0
16/16	53.5	54.5	54.0
18/16	54.0	54.0	54.0
20/16	53.8	53.8	53.8
22/16	53.3	53.3	53.3
24/16	53.0	55.0	54.0
26/16	53.0	53.0	53.0
28/16	52.0	54.0	53.0
30/16	51.0	55.0	53.0
32/16	50.0	54.0	52.0
36/16	51.3	51.3	51.3
40/16	50.0	52.0	51.0
44/16	51.4	51.0	51.2
48/16	51.0	52.0	51.5
52/16	52.0	52.0	52.0
56/16	50.0	54.0	52.0
60/16	51.0	53.0	52.0

Table 16 --- Specimen heated to 1700° F. for three hours.

Distances from quenched end, in.	Hardness readings, Rockwell C		
	On one side	On the other side	Ave.
1/16	48.0	47.0	47.5
2/16	55.8	55.0	55.4
3/16	54.5	54.5	54.5
4/16	54.0	54.0	54.0
5/16	53.8	53.8	53.8
6/16	53.9	53.3	53.6
7/16	56.0	52.0	54.0
8/16	54.4	54.0	54.2
9/16	55.5	55.5	55.5
10/16	53.6	54.0	53.8
11/16	56.0	54.0	55.0
12/16	54.5	54.5	54.5
13/16	56.0	56.0	56.0
14/16	58.0	54.0	56.0
15/16	58.0	52.0	55.0
16/16	55.0	57.0	56.0
18/16	54.0	55.0	54.5
20/16	54.0	54.0	54.0
22/16	55.0	55.0	55.0
24/16	57.0	53.0	55.0
26/16	54.0	54.0	54.0
28/16	53.0	55.0	54.0
30/16	52.0	52.0	52.0
32/16	51.0	53.0	52.0
36/16	52.0	52.0	52.0
40/16	56.0	50.0	53.0
44/16	52.4	52.0	52.2
48/16	51.0	53.0	52.0
52/16	52.0	52.0	52.0
56/16	51.0	52.0	51.5
60/16	51.0	51.0	51.0

Table 17 --- Specimen heated to 1950° F. for two hours.

Distances from quenched end, in.	Hardness readings, Rockwell C		
	On one side	On the other side	Ave.
1/16	42.0	44.0	43.0
2/16	49.0	47.0	48.0
3/16	50.5	51.5	51.0
4/16	54.0	52.0	53.0
5/16	52.5	55.5	54.0
6/16	54.5	54.5	54.5
7/16	53.5	55.5	54.5
8/16	53.5	55.5	54.5
9/16	56.0	53.0	54.5
10/16	55.0	54.0	54.5
11/16	52.6	55.0	53.8
12/16	53.6	54.0	53.8
13/16	55.4	52.2	53.8
14/16	53.0	56.0	54.5
15/16	54.0	54.0	54.0
16/16	55.0	53.0	54.0
18/16	53.0	53.0	53.0
20/16	53.0	52.0	52.5
22/16	51.5	53.5	52.5
24/16	52.0	55.0	53.5
26/16	53.0	51.0	52.0
28/16	52.5	51.5	52.0
30/16	52.0	53.0	52.5
32/16	51.5	52.5	52.0
36/16	50.0	52.0	51.0
40/16	51.0	51.0	51.0
44/16	51.0	49.0	50.0
48/16	48.0	52.0	50.0
52/16	50.0	51.6	50.8
56/16	51.0	50.0	50.5
60/16	50.0	52.0	51.0

Table 18 --- Specimen heated to 1950°F. for three hours.

Distances from quenched end, in.	Hardness readings, Rockwell C		
	On one side	On the other side	Ave.
1/16	44.0	46.0	45.0
2/16	52.0	50.0	51.0
3/16	54.0	53.0	53.5
4/16	53.5	54.5	54.0
5/16	52.0	54.0	53.0
6/16	53.5	53.5	53.5
7/16	51.5	54.5	53.0
8/16	51.5	53.5	52.5
9/16	54.0	53.0	53.5
10/16	53.5	53.5	53.5
11/16	54.0	52.0	53.0
12/16	55.0	55.0	55.0
13/16	53.0	53.0	53.0
14/16	51.5	55.0	53.0
15/16	52.5	52.5	52.5
16/16	52.0	54.0	53.0
18/16	54.0	52.0	53.0
20/16	51.0	55.0	53.0
22/16	51.0	53.0	52.0
24/16	52.0	55.0	53.5
26/16	53.0	54.0	53.5
28/16	52.0	54.0	53.0
30/16	52.0	53.0	52.5
32/16	51.5	53.5	52.5
36/16	52.0	51.0	51.5
40/16	51.0	51.0	51.0
44/16	50.0	52.0	51.0
48/16	50.5	51.5	51.0
52/16	50.0	51.0	50.5
56/16	50.0	53.0	51.5
60/16	51.0	53.0	52.0

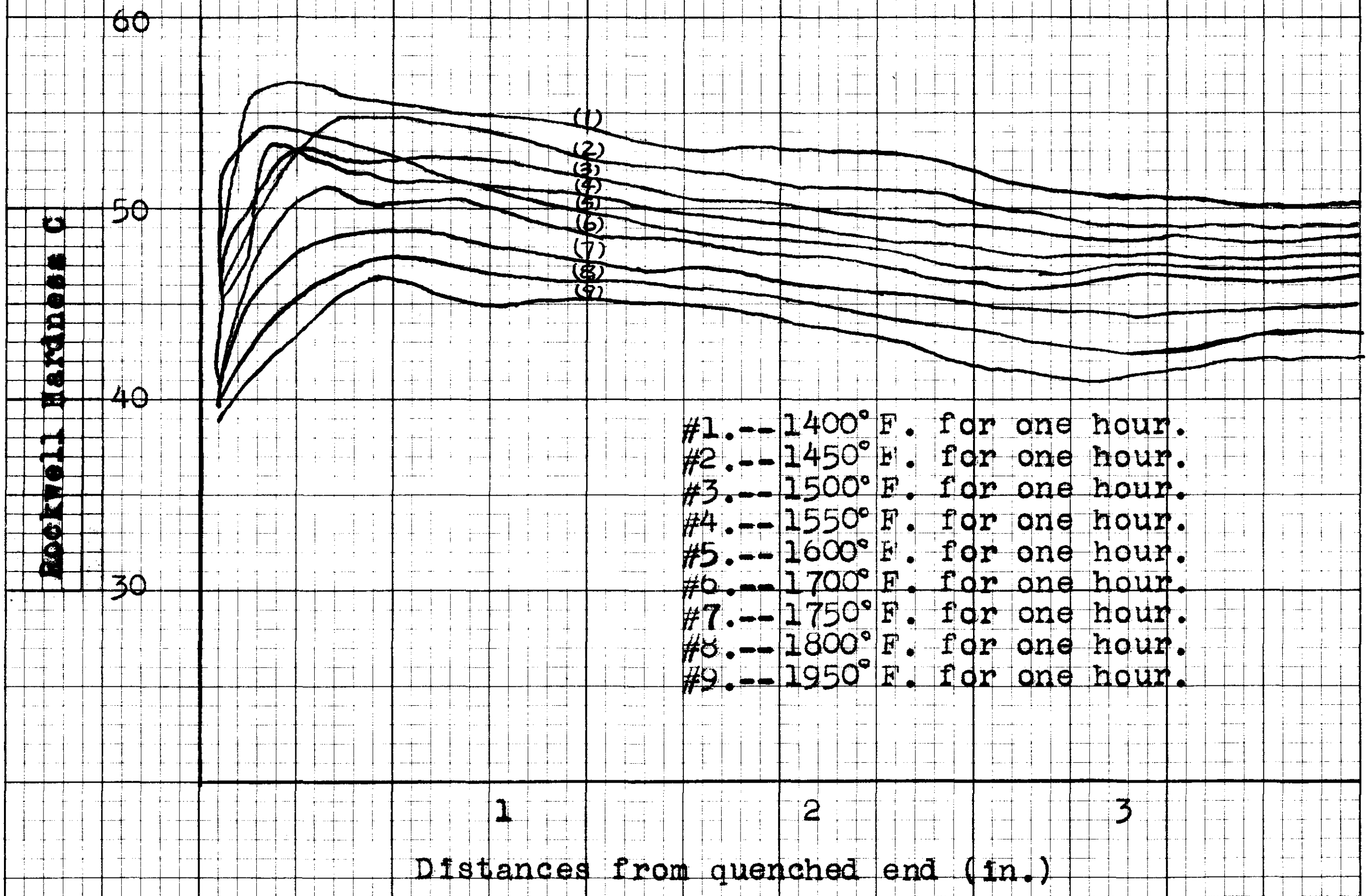

Fig. 3 --- Hardness against distances from quenched end.

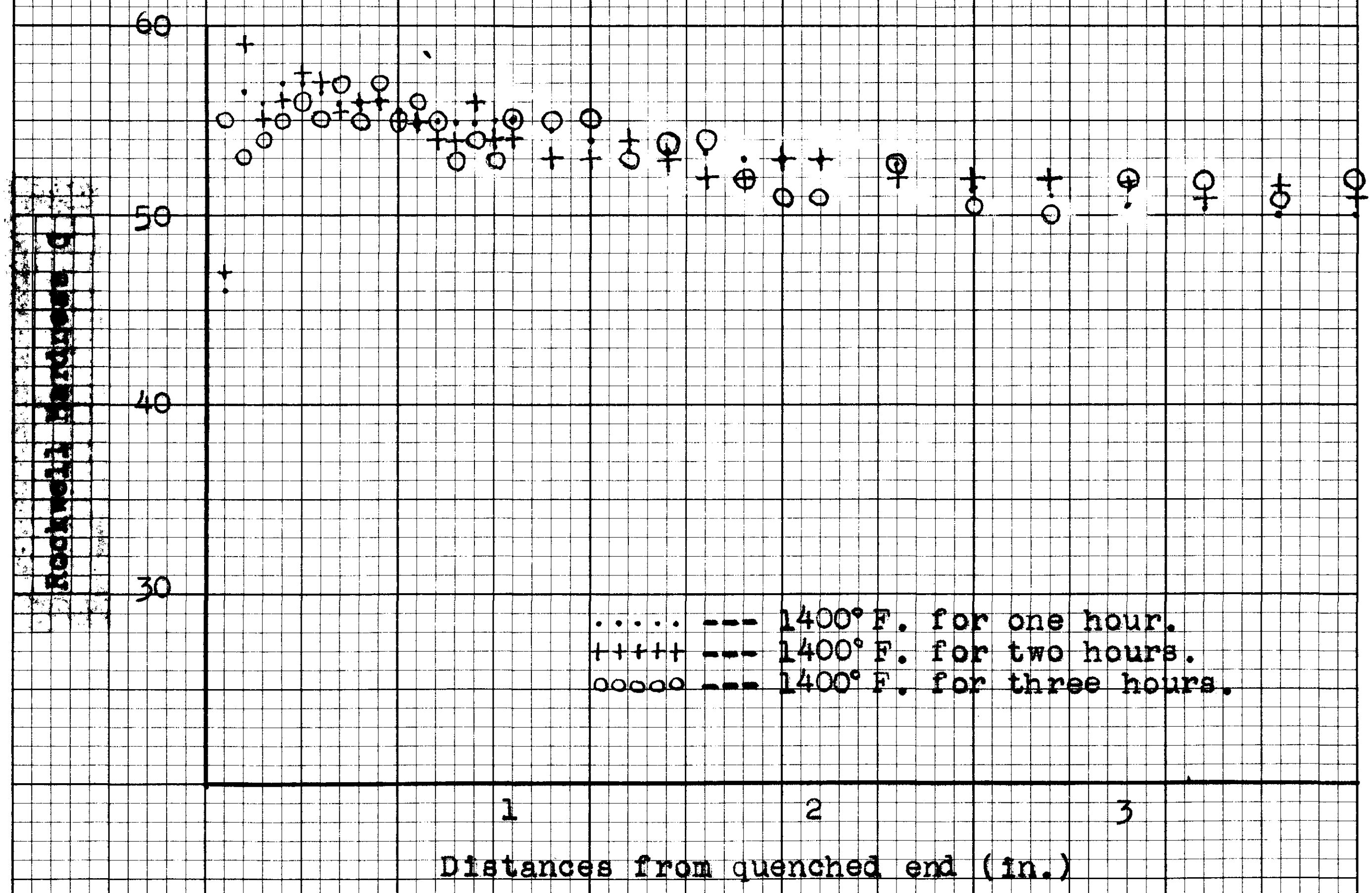

Fig. 4 --- Hardness against distances from quenched end.

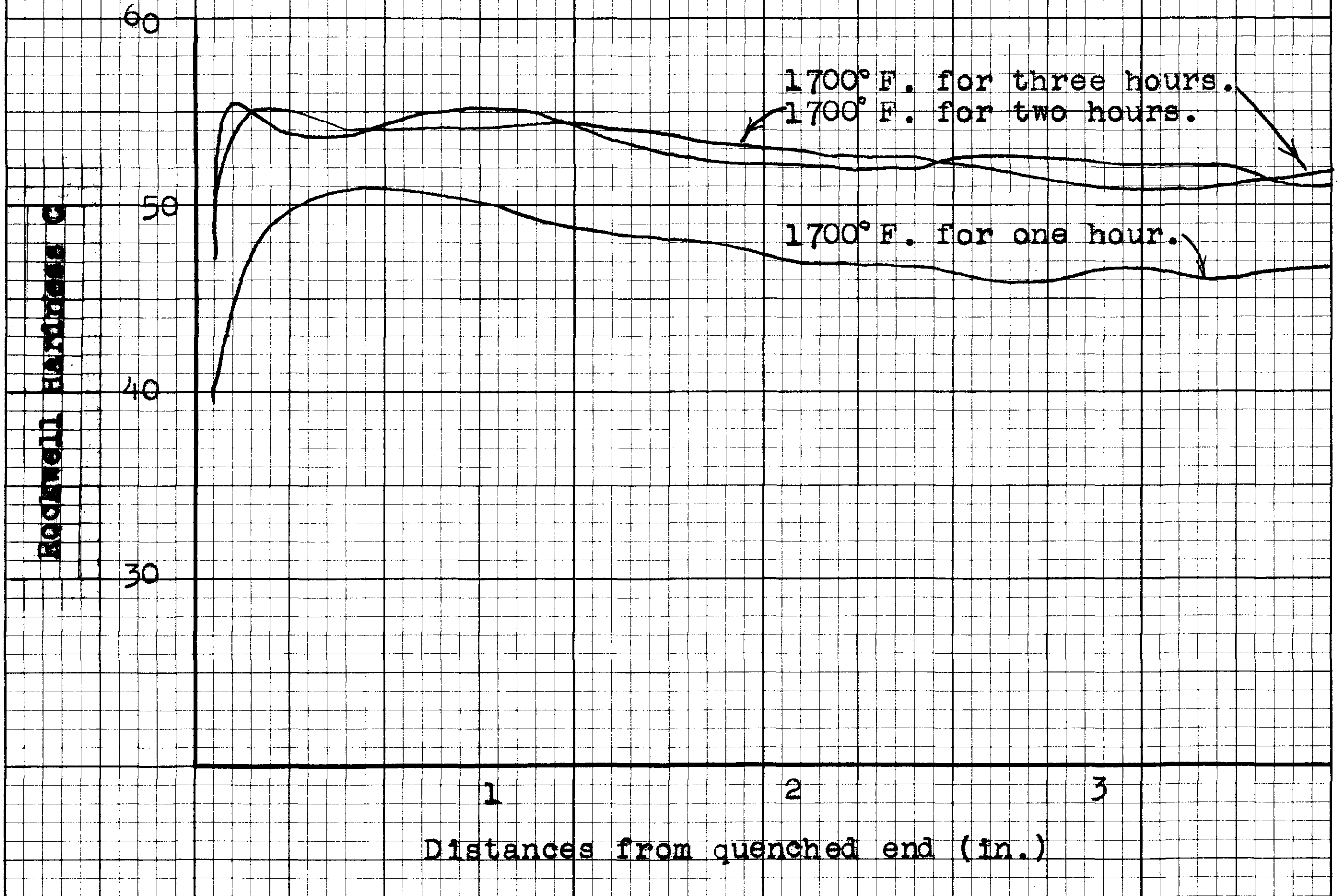

Fig. 5 --- Hardness against distances from quenched end.

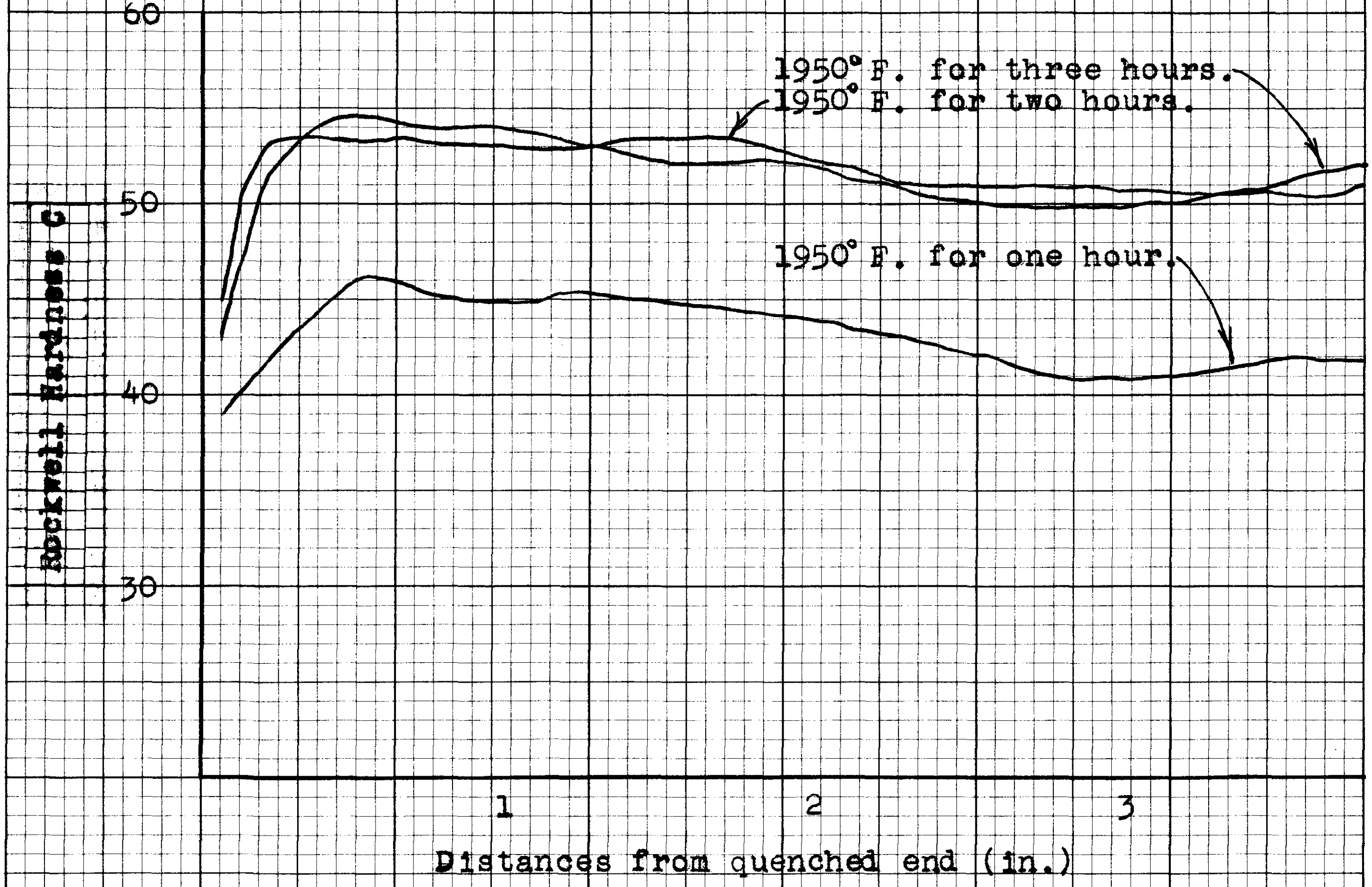

Fig. 6 --- Hardness against distances from quenched end.

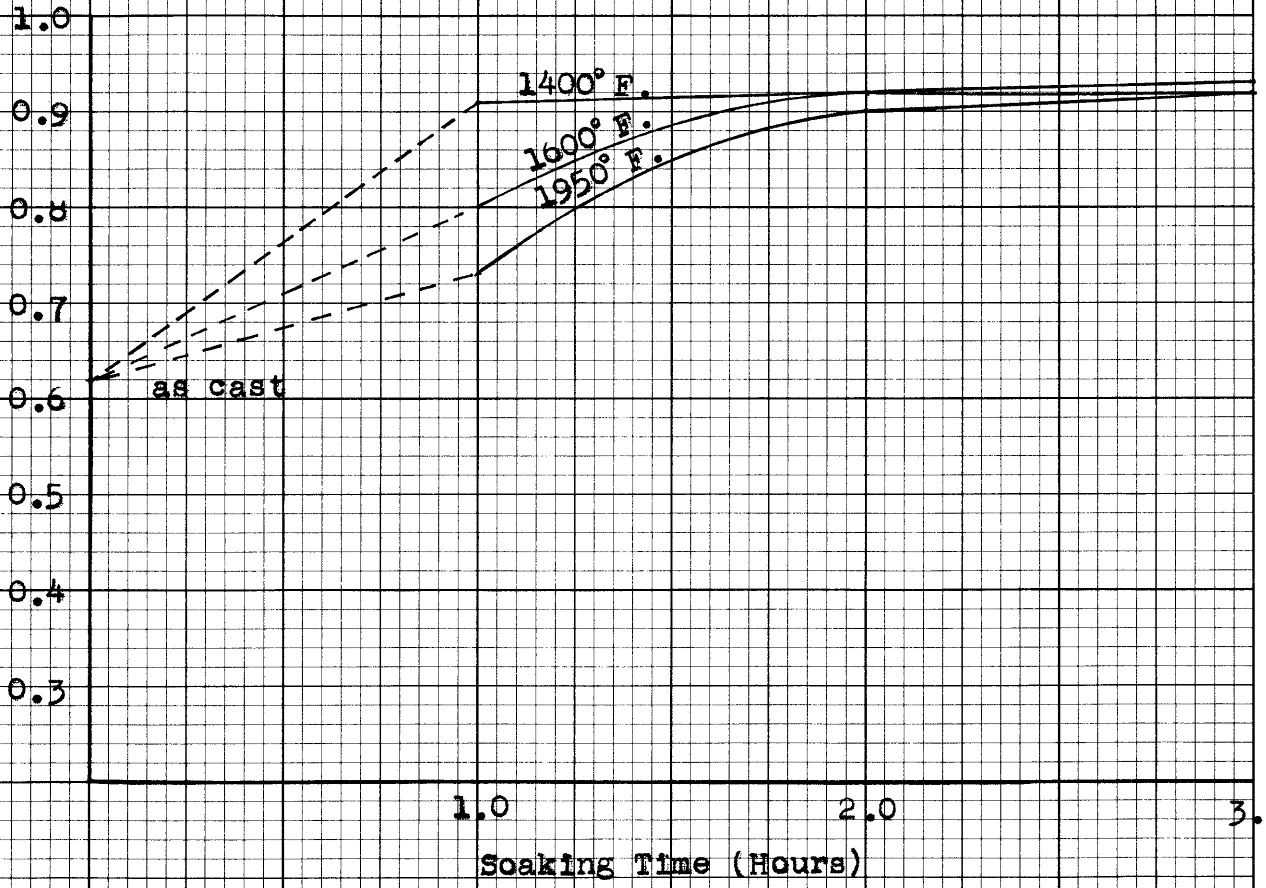

Fig. 7 --- Combined carbon content against soaking time.

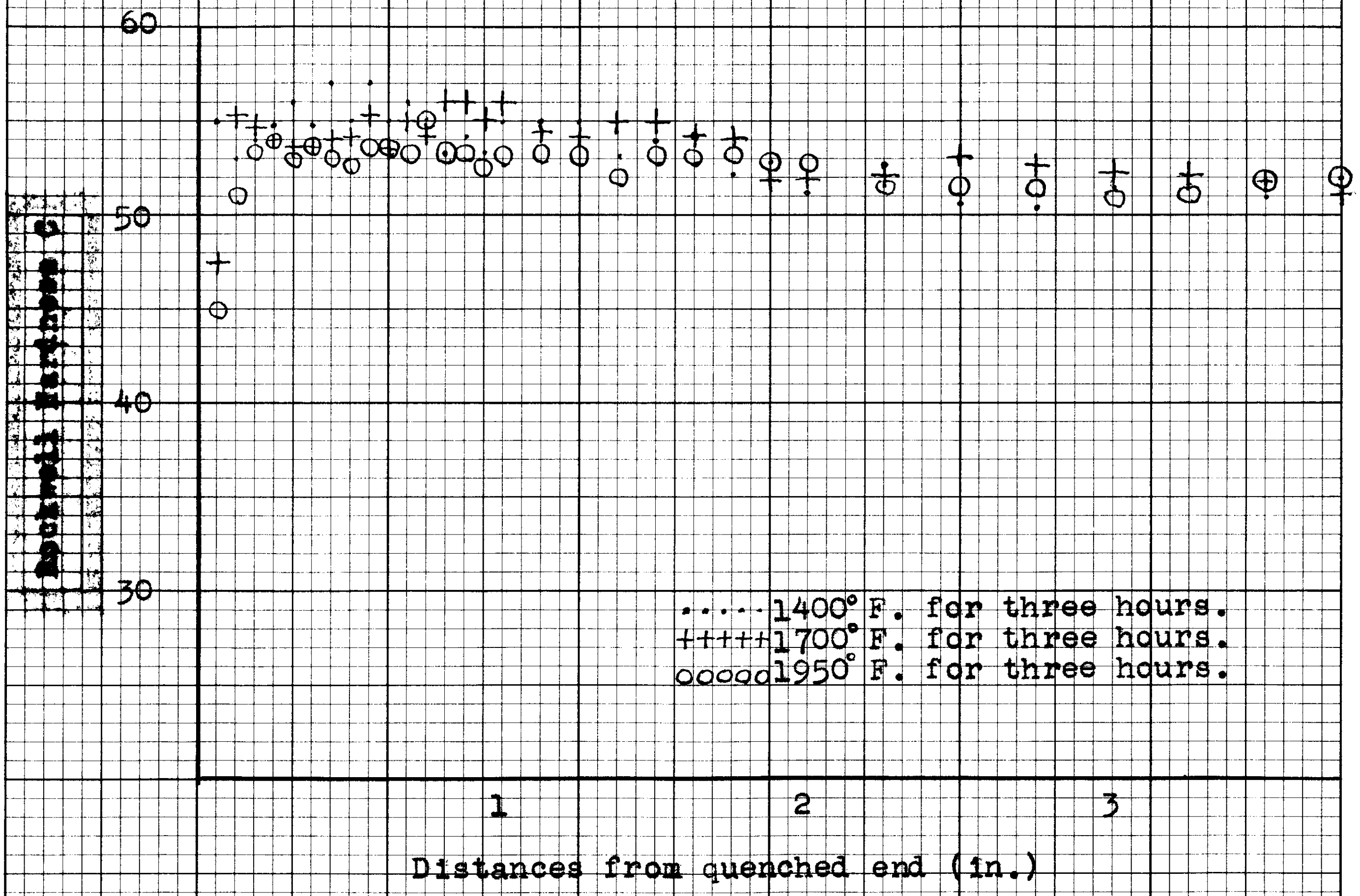

Fig. 8 --- Hardness against distances from quenched end.

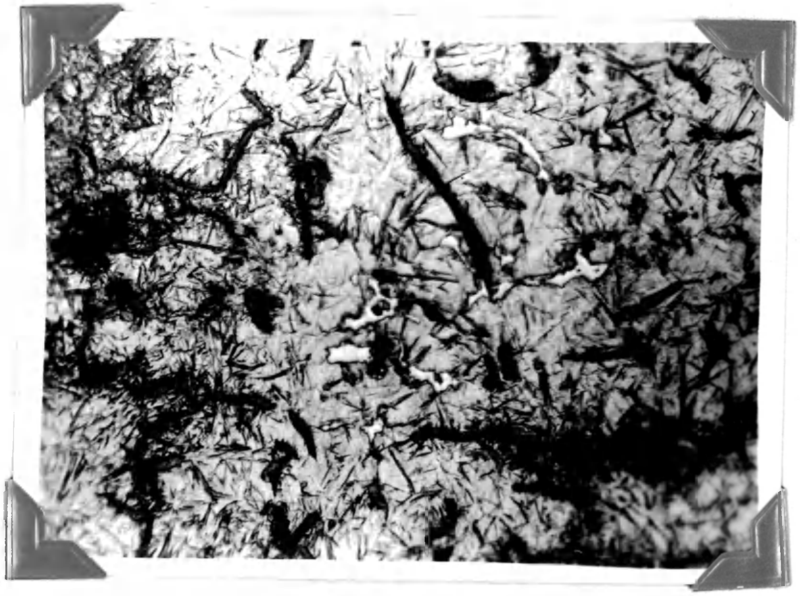

Fig. 9 --- Microstructure of specimen heated to 1400° F. for one hour. 250 X.

Fig. 10 --- Microstructure of specimen heated to 1950° F. for one hour. 250 X.

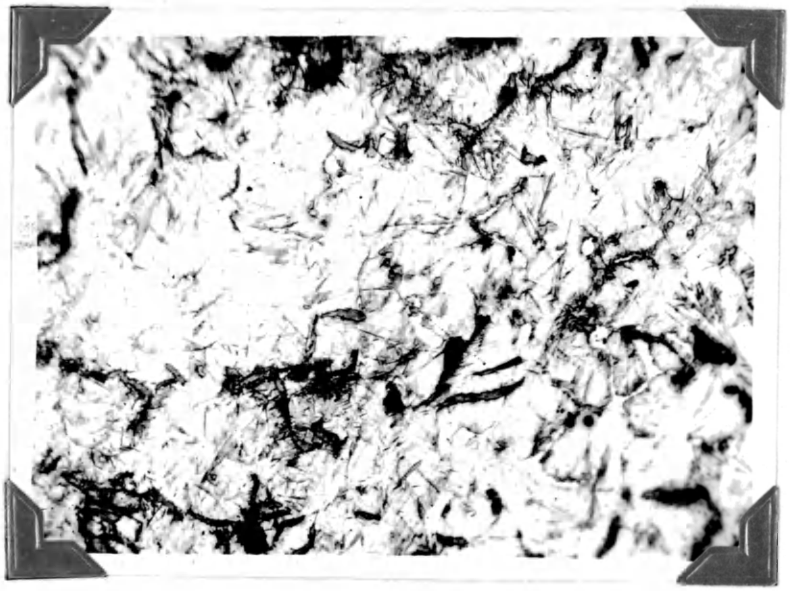

Fig. 11 --- Microstructure of specimen heated to 1400° F. for three hours. 250 X.

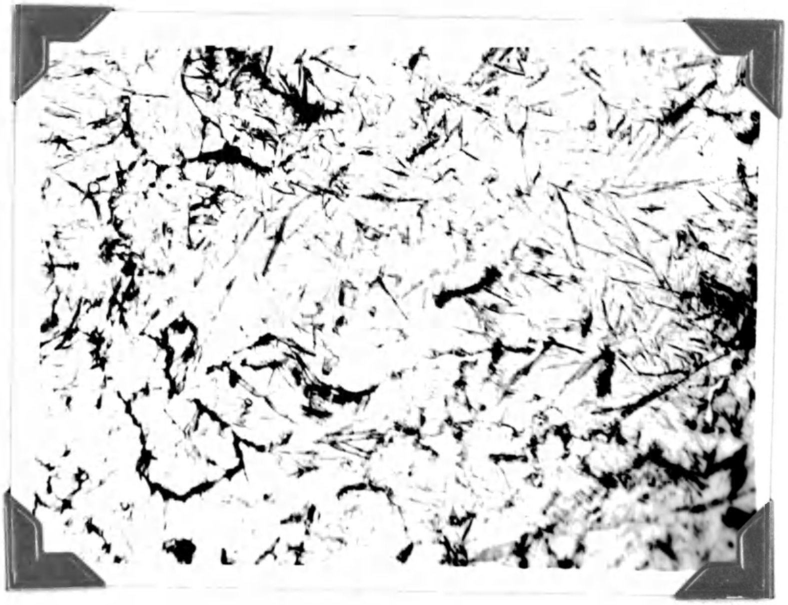

Fig. 12 --- Microstructure of specimen heated to 1950° F. for three hours. 250 X.

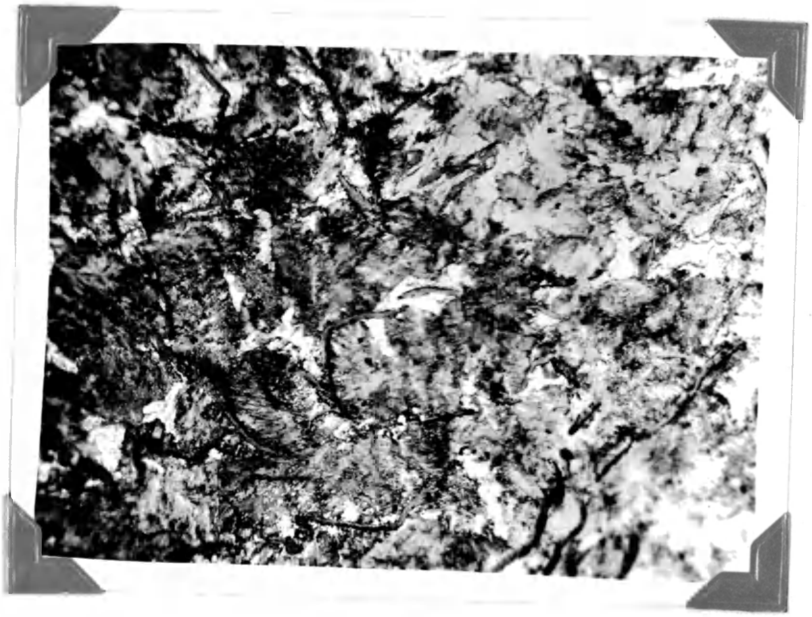

Fig. 13 --- Microstructure of specimen in the cast condition, etched with 5 percent picral. 250 X.

Fig. 14 --- Microstructure of specimen in the cast condition, unetched. 100 X.

Conclusions

The results obtained so far can be summarized as follows:

1. The hardenability of the material tested is high because it contains many alloy elements, which increase the hardenability by shifting the S curve (not determined yet) to the right and retarding the decomposition of austenite.

2. With soaking time of one hour, the lower the quenching temperature, the higher the hardness, as well as the higher the combined carbon content, because of the formation of spheroidized cementite during slow heating process, and these spheroides remained unchanged at low temperatures.

3. With high constant temperature, the longer the soaking time, the higher the hardness, as well as the higher the combined carbon content. But when the soaking time was long enough, say, two hours or longer, the hardness as well as the combined carbon content reached a constant. Moreover, when the temperature was not high enough, say, 1400° F., longer soaking time did not affect the hardness and the combined carbon content. This is because the soaking time of three hours or less did not

cause the decomposition of cementite, but did cause more graphitic carbon to dissolve in austenite at high temperatures, thus making the resulting martensite harder when quenched.

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