AN INVESTIGATION OF THE EFFECT OF HEAT TREATMENT UPON THE HARDNESS, MICROSTRUCTURE, AND COMBINED CARBON CONTENT OF SOME NODULAR CAST IRONS

by

James H. Barnett

ProQuest LLC.
789 East Eisenhower Parkway
P.O. Box 1346
Ann Arbor, MI 48106 – 1346

A thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Master of Science.

Signed:

James H. Barnett

James H. Barnett

Approved:

Clark B. Carpenter

Clark B. Carpenter

Morton C. Smith

Morton C. Smith

Golden, Colorado

Date May 7, 1951

ACKNOWLEDGMENT

The author wishes to acknowledge and express his most sincere appreciation to Professors Clark B. Carpenter and Morton C. Smith of the Department of Metallurgy for their patient guidance and expert counselling during the progress of this work.

CONTENTS

	Page
Introduction.	1
Experimental Procedures and Equipment	4
Preparation of Specimens	4
Heating, Soaking, and Quenching	4
Hardness Measurements	5
Microstructure Examinations	5
Specimen Analyses	6
Total Carbon Determination	7
Graphitic Carbon Determination	8
Combined Carbon Determination	9
Physical Testing	9
Experiments Using Mg-Si Nodular Iron	11
Discussion of Results	14
Hardness Tables	19
Tables of Carbon Content	21
Photomicrographs	22
Experimental Curves	26
Experiments Using Mg-Ni Nodular Iron	30
Discussion of Results	33
Hardness Tables	37
Tables of Carbon Content	39
Photomicrographs	40
Experimental Curves	43

CONTENTS (Continued)

	Page
Experiments on Heat Treating	47
Introduction	47
Methods and Equipment Used	50
Experimental Results	54
Discussion of Results	56
Hardness Tables	59
Photomicrographs	60
Stress-strain Curves	61
Conclusions	63
Bibliography	65

INTRODUCTION

Cast irons in which the graphitic carbon appears as spheroidal particles in the as-cast condition have become more commonly known today as ductile or nodular cast irons. The mechanism of the formation of this nodular graphite is at present not clearly understood, and various explanations of this phenomenon have been advanced by investigators in the field of metallurgy [1,2,3].

In normal gray cast iron, the graphitic carbon, which confers upon the material its characteristic properties of brittleness, non-ductility, and non-malleability, is in the form of flakes or lamellae of various sizes, depending upon casting section size, rate of cooling, composition, and melting procedure. These graphitic flakes interrupt the continuity of the metallic matrix, have a very low tensile strength, adhere weakly to the metallic matrix, and, by acting as stress raisers, reduce the mechanical properties of the aggregate. In nodular irons, the graphitic carbon is present in the form of nodules which are roughly spheroidal in shape; therefore, in contrast to the flake graphite in normal gray cast irons, do not interrupt to any marked degree the continuity of the metallic matrix. A material of relatively good shock resistance, ductility, and malleability is therefore obtained [4].

Various investigators have shown that nodular irons may be produced by use of any one of a number of addition agents, added while the iron is molten [5]. In all cases,

however, the physical and mechanical properties of the resulting nodular irons have been so greatly improved over those of normal gray cast irons that the field of use of cast irons in general has been greatly widened, and to date has not been completely determined. Some of the properties of nodular irons in the heat-treated state are actually higher than figures quoted for malleable irons and are almost comparable to the properties of cast steel. These facts have brought about the use of nodular irons in many applications heretofore considered to be beyond the scope of cast irons [6].

Structurally, nodular cast iron is a cast, high-carbon, ferrous product, free from graphite in the flake form. This type of iron is not a single material: it is actually a family of materials in which the matrix may be ferritic, pearlitic, martensitic, or austenitic. It has properties that vary according to the matrix structure. Any of the conventional methods for heat-treating ferrous materials are applicable to nodular irons, and by means of the proper heat-treatment a variety of mechanical property combinations may be developed in nodular irons. For example, simple annealing develops ferritic structures with a good tensile strength and a high percent elongation; normalizing and tempering will develop very high yield and tensile strengths with a slight degree of elongation; quenching or quench-and-temper treatments can be used to develop even higher levels of strength with little elongation.

At the present time, there is practically no published material available which describes the changes in microstructure and hardness of nodular cast irons as a result of direct quenching from various temperatures, both above and below the critical temperature of the material. It is for the purpose of securing such information that this thesis problem is being undertaken.

The major purposes of this problem are:

1. To determine the effect of soaking time and quenching temperature upon the microstructure, combined carbon content, and hardness of several nodular cast irons.

2. To determine whether nodular cast irons which were nodulized by using different nodulizing compounds behave in the same manner upon being quenched from the same temperatures.

EXPERIMENTAL PROCEDURES AND EQUIPMENT USED

In order to determine the effects of different soaking times and quenching temperatures upon the microstructure, combined carbon content, and hardness of nodular irons, which were produced by using different nodulizing agents, the following operations were conducted upon samples of two different nodular cast irons.

Preparation of Specimens

Samples of the nodular irons to be used in this phase of the experimental work were furnished in the form of 1-inch-diameter rounds, about ½-inch thick, just as they had previously been cut from standard arbitration bars. Due to the small number of samples of one of the nodular irons available, it was decided to increase the number of samples available for heat-treating by sub-dividing each of the rounds into two equal parts. This was accomplished by means of a hand hacksaw, and the cuttings from this operation were collected and saved for subsequent carbon determinations. It was also felt that by further decreasing the size of samples used it would be possible to more nearly attain in quenched specimens conditions approaching those which existed in the specimen just prior to quenching.

Heating, Soaking, and Quenching

All specimens were heated to temperature and soaked in a resistance-type, electric furnace equipped with temperature indicator and automatic temperature control. All specimens

were exposed to the furnace atmosphere during the heating and soaking periods. At each of the soaking temperatures used (1200 F, 1400 F, 1600 F, and 1800 F), specimens of each type of nodular iron were soaked for periods of 1, 2, 4, and 8 hours. Prior to placing specimens in the furnace, the furnace was brought to the desired temperature. After the specimens had been placed in the furnace, 15 minutes were allowed for them to attain the desired temperature before timing of the soaking period was begun. Upon completion of the desired soaking period, specimens were removed from the furnace and quenched in cold tap-water.

Hardness Measurements

After quenching, one of the flat sides of each specimen was ground, by means of a coarse grinding wheel and a belt sander, to a depth sufficient to insure the removal of any decarburized zone. The specimen was kept cool enough during this grinding to prevent any tempering. Hardness readings were then taken on this smooth, flat surface using the C scale on a Rockwell hardness testing machine. Due to the shape of the specimens used, hardness surveys were made in the pattern shown in Figure 2 (p. 22). From the average hardness values obtained, curves were plotted showing the effect of different soaking times and quenching temperatures upon the hardness of different nodular irons.

Microstructure Examinations

To observe the effects of different soaking times and quenching temperatures upon the microstructure of nodular

cast irons, each specimen, after being quenched and tested for hardness, was ground, polished, etched, and examined microscopically. Photomicrographs of specimens which showed the greatest effect of time and temperature were then taken. In all temperature ranges, the specimen which showed the greatest effect of temperature was the one which had been exposed to that temperature for the longest period of time; therefore, only photomicrographs of heat-treated specimens which were soaked for 8-hour periods are included as a part of this thesis.

Specimen Analyses

In order to determine the effects of soaking time and quenching temperature upon the combined carbon content of the differently heat-treated specimens, graphitic carbon analyses of each were made. Total carbon analyses of each iron in the as-cast condition were made. The combined carbon content of each specimen was then determined by difference between total and graphitic carbon contents.

Clean, representative samples of each specimen were obtained and used in all analyses. In cases where the carbon content determined by this method was of doubtful accuracy, several analyses of the same sample were run in order to assure accurate, average results.

The direct combustion method of analysis was used in both total carbon and graphitic carbon determinations. The combustion train used (Fig. 1, p. 22) was of standard design and consisted of an oxygen source, oxygen-purifying train,

combustion furnace, combustion-product purifying train, and a CO_2 absorber. The oxygen source was a small, high-pressure tank of welding oxygen (U.S.P.). The oxygen-purifying train was made up of a water absorption tube of concentrated H_2SO_4, a CO_2 absorption tube of Ascarite and Drierite, and a second absorption tube of Drierite. The combustion furnace used was a tube furnace of the electric-resistance type, in series with a rheostat for temperature control. The combustion-product purifying train was made up of a water absorption tube of concentrated H_2SO_4 and a tube of Drierite. The CO_2 absorber used contained Ascarite to absorb CO_2 and Drierite to absorb moisture evaporated from the CO_2 absorbent by the oxygen stream flowing through it.

Total Carbon Determination

The samples of nodular iron used in the total carbon analyses consisted of hacksaw cuttings, all of which were minus 10-mesh in size, obtained when cutting the specimens in preparation for heat-treatment. Each determination was made using a sample which weighed 1.3636 grams. After weighing, each 1.3636 gram sample was placed in a nickel combustion boat, which had previously been filled about two-thirds full of alundum, 0.2 gram of finely divided tin was sprinkled on the sample, a thin covering of alundum sprinkled on top, and the boat placed in a tube furnace which was maintained at a temperature of 1000 C to 1400 C. A stream of purified oxygen was passed over the sample for 12 minutes to assure complete combustion in the furnace.

The gaseous products of this combustion were passed through an absorption bulb containing soda asbestos (Ascarite) which absorbed the CO_2 from these combustion products. After 12 minutes, the flow of oxygen was shut off, the absorption bulb disconnected from the combustion train, and carefully weighed to determine the weight of CO_2 absorbed by the bulb. Since a 1.3636 gram sample of iron was used in the determination, the weight of CO_2 absorbed was multiplied by 20 to obtain the percentage of carbon in the original material. In the case of each nodular iron used in this work, six separate total carbon analyses were run to assure an accurate average value for the total carbon content. The average of these six determinations was then used in determining combined carbon contents.

Graphitic Carbon Determination

In the determination of graphitic carbon content, a sample as near to 1.3636 grams in weight as could be conveniently obtained was sawed from each heat-treated specimen. These samples were accurately weighed, then were dissolved in 50 ml of 6N nitric acid. The solution obtained was then filtered through an asbestos filter in a Gooch crucible; the residue washed with hot water, then with a hot solution of potassium hydroxide (d 1.1), followed by hot water, dilute hydrochloric acid, and finally with hot water until free from chlorides. The contents of the Gooch crucible were then transferred to a nickel combustion boat in which there was a bed of alundum, a thin cover of alundum sprinkled on top,

the boat placed in the tube furnace, and treated in the manner previously described for total carbon determination. After combustion was complete, the absorption bulb was weighed to obtain the weight of CO_2 absorbed. The percentage of graphitic carbon in the sample was then calculated by using the following formula:

$$\% \text{ G.C.} = \frac{\text{At. wt. of carbon}}{\text{Mol. wt. of } CO_2} \times \frac{\text{Wt. of } CO_2 \text{ absorbed}}{\text{Wt. of sample used}} \times 100$$

Determination of Combined Carbon

The combined carbon content of each iron in the as-cast condition, and of each heat-treated specimen, was determined by subtracting the percentage of graphitic carbon in the sample from the percentage of total carbon in the iron as-cast. From the percentages of combined carbon thus obtained, curves were plotted showing the effect of soaking time and quenching temperature upon the combined carbon content of each of the nodular irons used.

Physical Testing

In order to determine some of the important properties of the nodular irons used in this work, tensile tests of the irons were conducted. Since there were only six tensile specimens available - these six having been furnished by the International Nickel Company - all physical testing was limited to this iron. Two of these specimens were tested in the as-cast condition, two in the heat-treated and slow-cooled condition, and two in the quenched-and-tempered condition.

After the specimens had been heat-treated in an electric, resistance-type furnace, Brinell hardness readings were taken at several points on each specimen; and they were then broken in tension in a hydraulic testing machine of 120,000 pounds capacity. During testing, elongation measurements were made after each 2000-pound increment of load had been applied; and from the information thus obtained stress-strain curves for Mg-Ni nodular iron in the differently heat-treated conditions were plotted.

EXPERIMENTS USING NODULAR IRON PREPARED BY USING A Mg-Si NODULIZING AGENT

Introduction

The first phase of this experimental work was conducted using samples of nodular cast iron prepared by Vishwanath A. Altekar as part of the work for the Master's Thesis entitled "Investigation of Production and Properties of Nodular Cast Iron". This iron was prepared by using a nodulizing agent which contained 15% magnesium and 50% silicon. The analysis of this iron was as follows: T.C. 2.85%, G.C. 2.35%, C.C. 0.50%, Si 2.55%, and S 0.02%.

Heating, Soaking, and Quenching

Specimens of Mg-Si nodular cast iron were heated, soaked, and quenched in the manner described (p. 4) under Experimental Procedures.

Hardness Measurements

After the specimens were quenched, hardness readings were taken. Table 1 (pp. 19-20) gives the tabulated experimental hardness readings obtained. From the data thus obtained, curves (Figs. 9-10, pp. 26-27) were plotted.

Carbon Analyses

Each specimen, after quenching, was analyzed for graphitic carbon. The as-cast specimen was also analyzed for total carbon. The combined carbon content of each specimen was then obtained as the difference between total carbon and graphitic carbon. The experimental results obtained are

shown in Table 2 (p. 21). From the results shown in Table 2, curves (Figs. 11-12, pp. 28-29) were plotted.

Microstructure Examinations

Figure 3 (p. 23) shows the microstructure of the Mg-Si nodular iron in the as-cast condition before etching. In it may be seen the graphite nodules which vary in size from very small to about ASTM grain size 7. The average nodule size is about ASTM grain size 8.

Figure 4 (p. 23) shows the specimen microstructure in the as-cast condition after etching for 40 seconds with 2% nital. Each graphite nodule is seen to be completely surrounded by areas of ferrite. Between the areas of ferrite, areas of pearlite can be seen. The graphite nodules average slightly less than ASTM grain size 8 in size.

Figure 5 (p. 24) shows the microstructure after soaking at 1200 F for 8 hours. This photomicrograph shows that the matrix is essentially ferritic and that much of the pearlite which was present in the as-cast state has broken down into ferrite and spheroids of cementite. The average nodule size is slightly smaller than ASTM grain size 8.

Figure 6 (p. 24) shows the microstructure after soaking at 1400 F for 8 hours. In this photomicrograph, it may be seen that practically all the pearlite which was originally present has broken down into ferrite and spheroidized cementite. The matrix has become almost entirely ferritic. Spheroids of cementite are visible in sizes ranging from very small to medium. The average nodule size remains slightly

smaller than ASTM grain size 8.

Figure 7 (p. 25) shows the microstructure after soaking at 1600 F for 8 hours. The average nodule size has increased slightly so that it is now between ASTM grain size 8 and ASTM grain size 7. The matrix has become completely ferritic and no pearlite at all may be seen. Some extremely small spheroids of cementite can be seen at ferrite grain boundaries. Secondary graphite has begun to deposit on the original graphite nodules. It appears as roughened, serrated edges on the original nodules.

Figure 8 (p. 25) shows the microstructure after soaking at 1800 F for 8 hours. The matrix is martensitic and contains graphite nodules together with areas of retained austenite. The edges of the nodules are becoming diffuse, instead of even and distinct, which indicates that they are beginning to dissolve in the austenite. The average nodule size is slightly smaller than ASTM grain size 8.

DISCUSSION OF EXPERIMENTAL RESULTS

Effect of Quenching Temperature Upon Hardness

From the experimental results shown in Table 1 (pp. 19-20) and the curves (Figs. 9-10, pp. 26-27) drawn from these results, it can be seen that the hardness of this nodular iron remains essentially constant when the iron is quenched from 1200 F, reaches its minimum value at a soaking temperature of 1400 F, and begins to increase again as quenching temperatures above 1400 F are used.

The results obtained at a temperature of 1200 F are those that may be expected from the relief of residual stresses in a cast structure. In addition, at this temperature there is a decrease in the amount of pearlite visible under the microscope. At this temperature, pearlite will slowly break down into ferrite and spheroidized cementite which will tend to decrease the hardness of the iron to a slight degree.

At a quenching temperature of 1400 F, the breakdown of pearlite into ferrite and spheroidized cementite is more rapid and is more nearly complete in a given period of time than at lower temperatures. This fact partly accounts for lower hardness in a specimen after quenching from 1400 F than in the specimen in the as-cast condition. Hardness is further lowered by the breakdown of spheroidized cementite into ferrite and graphite which takes place at temperatures between 1165 F and 2190 F [7].

At a quenching temperature of 1600 F, the solution of carbon in iron had begun to proceed at a rate such that its

hardening effect was greater than the tendency to soften due to the breakdown of cementite into ferrite and graphite. A slight increase in hardness over that observed at 1400 F was therefore obtained.

At a quenching temperature of 1800 F, hardness values reached a maximum as martensitic structures were obtained, then began to decrease as larger amounts of retained austenite appeared in the quenched specimen. At this temperature, the solubility of carbon in austenite is higher than at any other quenching temperature used. It is also well known that the higher the carbon content of austenite the more retained austenite it is possible to obtain with drastic quenching. By referring to Table 2 (p. 21), it may be seen that at 1800 F the combined carbon content of this iron was steadily increasing as soaking times went from 1 to 8 hours. This increase in combined carbon therefore accounts for the greater amounts of retained austenite, which in turn accounts for the decrease in hardness of the specimen.

Effect of Soaking Time Upon Hardness

At a quenching temperature of 1200 F, the average hardness of the heat-treated specimens remained essentially constant as soaking time varied from 1 to 8 hours. Since this temperature is below the critical, no significant hardness changes in the specimens, other than those brought about by the relief of residual stresses and some spheroidization of cementite, were expected.

At 1400 F, the average hardness of the specimens de-

creased as soaking time was increased. This hardness decrease is explained by the fact that longer times at this temperature allow a more complete breakdown of pearlite and spheroidized cementite into ferrite and graphite.

At 1600 F, the average hardness of the specimens remained about the same even though the soaking time was increased from 1 to 8 hours. Even though a specimen was soaked for 8 hours at this temperature and then water quenched, its hardness was below that of an as-cast sample of the same iron. The low hardness of this nodular iron after such a heat-treatment is unusual and was completely unexpected since martensitic structures had been predicted. The only plausible explanation for this observed effect is that, due to the composition of the iron, its critical temperature has been raised to some point above 1600 F. In this case, even though it is held for a long period of time at a temperature at which most irons become austenitic, this particular iron does not do so.

At 1800 F, increasing periods of soaking time at first increase the hardness of the specimens then begin to decrease the hardness as soaking periods exceed two hours. This decrease in hardness is a result of increasing amounts of retained austenite present in specimens as lengths of soaking periods increase. The increasing amount of retained austenite obtained is due to the increasing carbon content of the austenite.

Effect of Quenching Temperature Upon Microstructure

Evidence of changes in microstructure caused by higher and higher quenching temperatures is given in Figures 3-8 (pp. 23-25). These photomicrographs show that at soaking temperatures of 1200 F, 1400 F, and 1600 F the matrix of the iron grows progressively more ferritic; and that the graphite nodules tend to increase slightly in size due to the deposition of secondary graphite on the previously existing nodules. Figure 8 (p. 25) shows that at a quenching temperature of 1800 F the original ferritic matrix has been converted to martensite. The fact that we have gotten martensite in the structure at this temperature, but not at any lower temperature, indicates that the critical temperature for this iron is somewhere between 1600 F and 1800 F. Figure 8 (p. 25) also shows that the graphite nodules have decreased in size, and that some of the austenite does not convert to martensite upon quenching so appears as retained austenite in the structure.

Effect of Soaking Time Upon Microstructure

Examination of the microstructure of all heat-treated specimens showed that structural changes in the specimens are a function of the quenching temperature; and that these changes move toward completion - which implies a move toward constituents which are stable at that temperature - as longer and longer soaking periods are allowed.

The only specimens which showed any deviation from this general rule were those that were soaked from 1 to 8 hours

at a temperature of 1600 F. Strictly speaking, however, the reactions of this iron at 1600 F were not deviations from this general rule. They were merely the normal reactions that may be expected when any iron is quenched from below its critical temperature. We must therefore modify our original statement and say that no true deviations from the general rule were noted.

It was noticed, however, that final traces of pearlite in the microstructure of this iron were very persistent and that soaking periods of several hours were required for its complete breakdown, even at 1600 F. Rehder, in his work on the annealing of nodular irons [8], has commented upon this fact.

Effect of Quenching Temperature Upon Combined Carbon

The combined carbon content of irons is a function of the composition of the iron, the temperature at which the iron has been held, the length of holding at temperature, and the manner in which the iron has been cooled from the soaking temperature. In this work, all specimens were quenched in such a manner that cooling was very rapid; and for all practical purposes no change in the combined carbon content of the specimens could have taken place. At all temperatures, except 1600 F, the trend of combined carbon content was in the direction expected for ferrous materials. Equilibrium conditions were not attained at any temperature, however, so no check on the solubility of carbon in iron can be made.

Table 1 Hardness Readings

Mg-Si nodular cast iron: Effect of Quenching Temperature and Soaking Time Upon Hardness.

Specimen Condition	Hardness (Rockwell C) at different points on the specimen.	Average Hardness
As cast	33.5, 30.5, 32.6, 34.0, 29.3, 32.3, 33.5, 30.5	32.0
Soaked at 1200 F for 1 hour	21.7, 25.4, 27.3, 27.8, 27.4, 22.7, 29.6, 28.8, 24.9	26.2
Soaked at 1200 F for 2 hours	26.5, 28.8, 27.6, 30.1, 31.2, 26.4, 29.7, 30.5, 26.4	28.6
Soaked at 1200 F for 4 hours	25.6, 27.2, 28.2, 28.8, 29.4, 30.0, 28.7, 27.4, 26.5	27.9
Soaked at 1200 F for 8 hours	24.6, 27.0, 28.0, 29.6, 28.1, 29.5, 27.5, 27.9, 29.5	27.9
Soaked at 1400 F for 1 hour	25.9, 27.6, 28.8, 26.0, 25.4, 26.4, 28.3, 26.3, 23.5	26.5
Soaked at 1400 F for 2 hours	23.9, 22.8, 24.5, 25.7, 23.3, 26.4, 24.5, 21.5, 23.5	24.0
Soaked at 1400 F for 4 hours	20.2, 25.5, 27.6, 24.3, 21.5, 23.3, 25.7, 25.3, 21.2	23.8
Soaked at 1400 F for 8 hours	20.0, 20.1, 22.0, 23.5, 24.0, 22.7, 22.3, 22.6, 19.0	21.8

Table 1. Hardness Readings (continued)

Mg-Si nodular cast iron: Effect of Quenching Temperature and Soaking Time Upon Hardness

Specimen Condition	Hardness (Rockwell C) at different points on the specimen.	Average Hardness
Soaked at 1600 F for 1 hour	25.3, 29.0, 27.6, 29.3, 28.2, 27.0	27.7
Soaked at 1600 F for 2 hours	28.8, 30.2, 29.0, 27.6, 31.4, 23.5, 30.0	28.6
Soaked at 1600 F for 4 hours	28.3, 27.4, 27.3, 25.0, 29.9, 26.0, 22.7	26.7
Soaked at 1600 F for 8 hours	28.5, 31.8, 30.7, 31.2, 26.9	29.8
Soaked at 1800 F for 1 hour	49.5, 48.6, 49.7, 50.9, 46.3, 50.6, 50.9, 50.4, 49.3	49.6
Soaked at 1800 F for 2 hours	53.8, 54.4, 53.9, 53.7, 54.5, 54.7, 54.4, 51.7, 50.3	53.5
Soaked at 1800 F for 4 hours	53.9, 53.3, 53.2, 53.8, 51.5, 52.0, 50.0, 53.3, 52.9	52.7
Soaked at 1800 F for 8 hours	51.7, 54.1, 53.5, 51.9, 52.1, 54.0, 52.5, 51.9, 51.4	52.6

Table 2 Carbon Analyses

Mg-Si nodular cast iron: Table showing varying combined carbon contents after soaking at different temperatures for several periods of time.

Specimen	Quenching Temp. (F)	Soaking Time (Hrs)	T.C. (%)	G.C. (%)	C.C. (%)
7 (As cast)			2.85	2.35	0.50
7G	1200	1	2.85	2.46	0.39
7H	1200	2	2.85	2.38	0.47
7I	1200	4	2.85	2.44	0.41
7J	1200	8	2.85	2.45	0.40
7A	1400	1	2.85	2.47	0.38
7K	1400	2	2.85	2.49	0.36
7L	1400	4	2.85	2.51	0.34
7B	1400	8	2.85	2.57	0.28
7E	1600	1	2.85	2.53	0.32
7M	1600	2	2.85	2.47	0.38
7N	1600	4	2.85	2.42	0.43
7F	1600	8	2.85	2.43	0.42
7C	1800	1	2.85	2.07	0.78
7O	1800	2	2.85	1.98	0.87
7P	1800	4	2.85	1.99	0.86
7D	1800	8	2.85	1.80	1.05

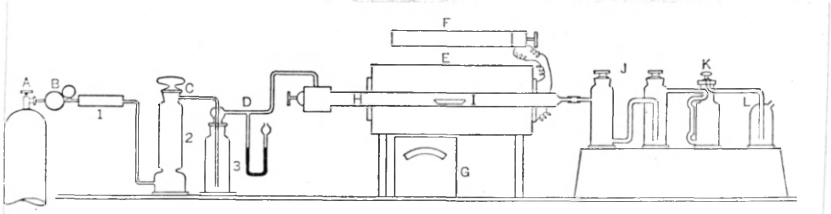


FIG. 41. Diagram of combustion train for the determination of carbon in steel.[1]

Figure 1

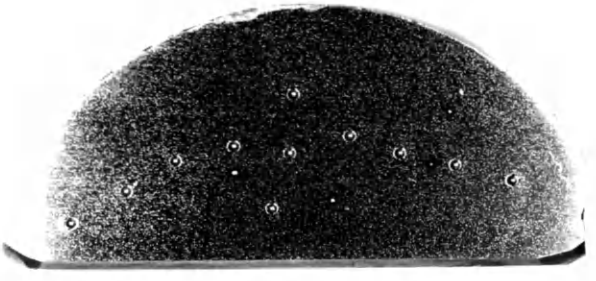


Figure 2. Hardness survey pattern
Magnified 2X

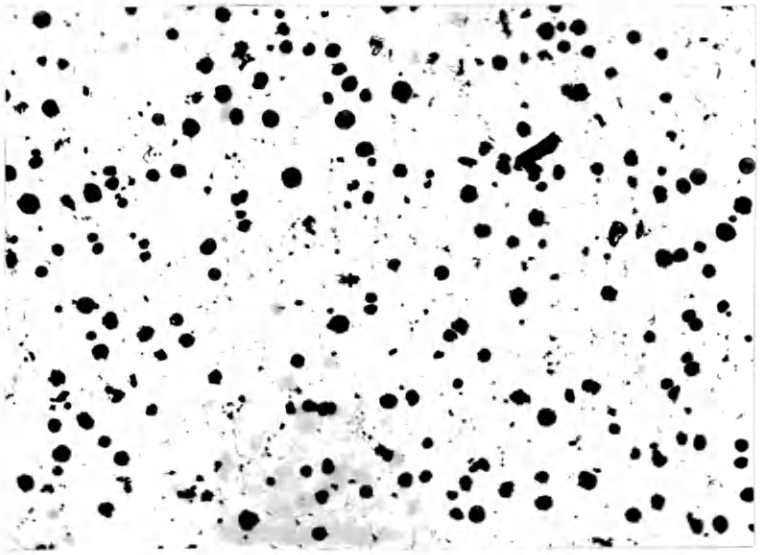


Figure 3. Mg-Si nodular cast iron, As-cast, Unetched
100X

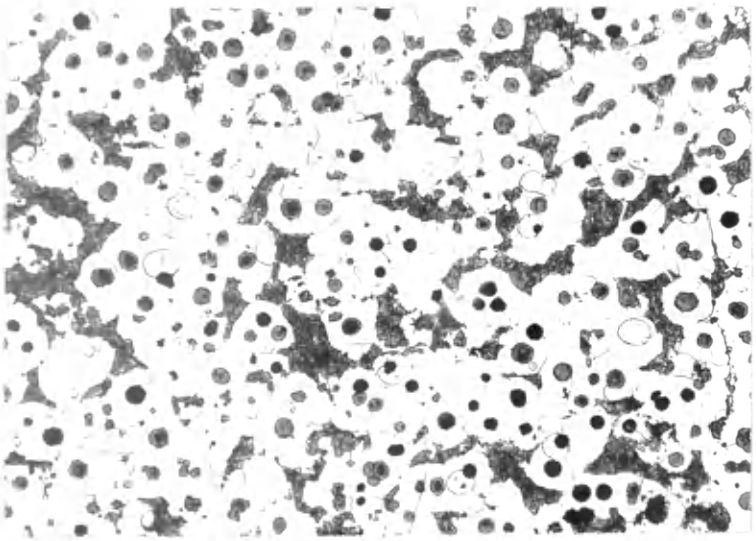


Figure 4. Mg-Si nodular cast iron, As-cast, Etched 40 seconds with 2% nital. Magnified 100X

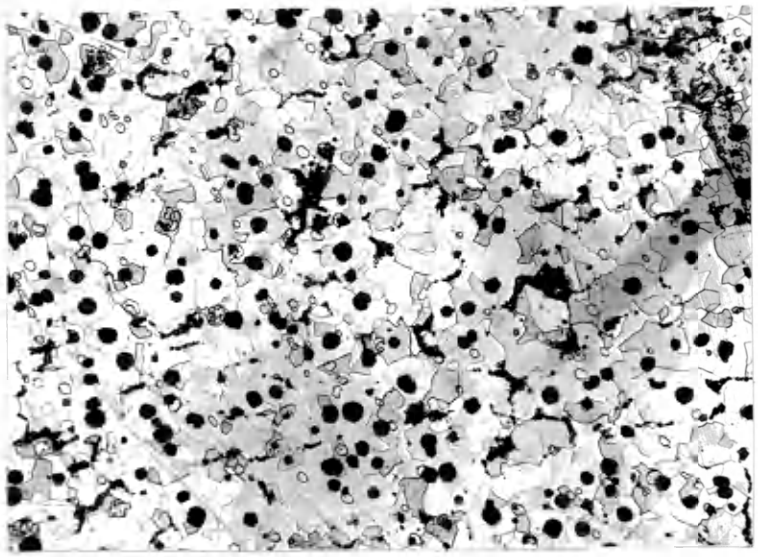


Figure 5. Mg-Si nodular cast iron, Soaked 8 hours at 1200 F, Water quenched, Etched 40 seconds with 2% nital. Magnified 100X

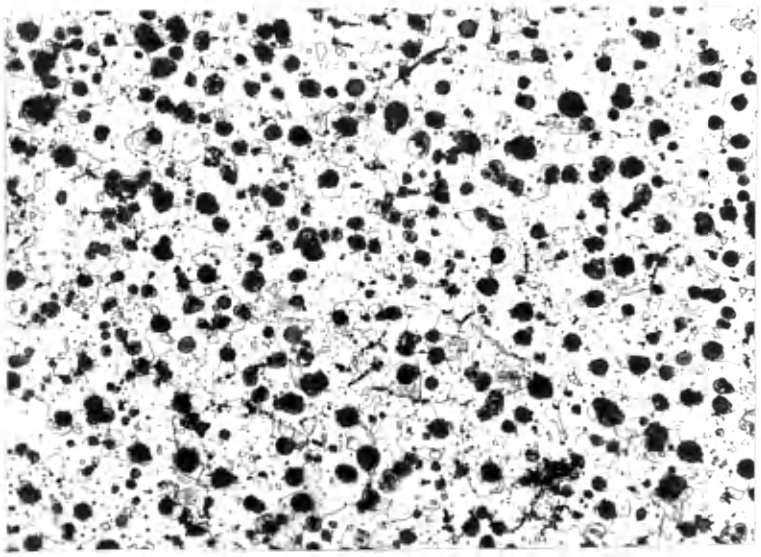


Figure 6. Mg-Si nodular cast iron, Soaked 8 hours at 1400 F, Water quenched, Etched 40 seconds with 2% nital. Magnified 100X

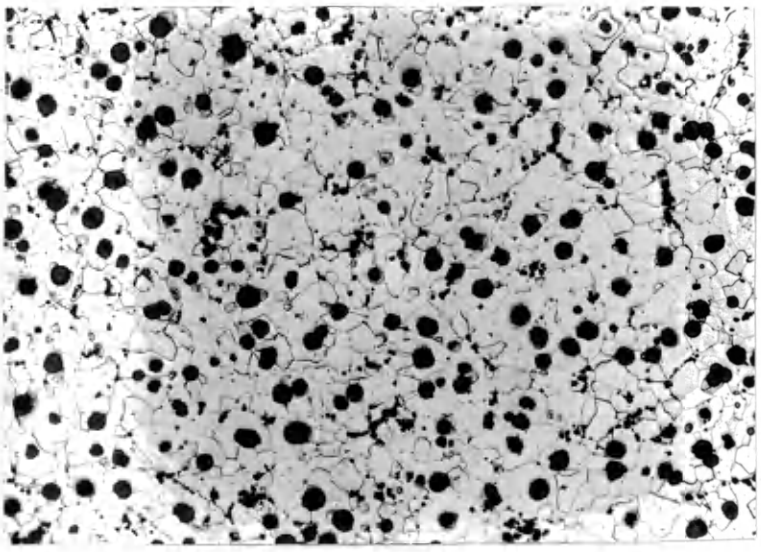


Figure 7. Mg-Si nodular cast iron, Soaked 8 hours at 1600 F, Water quenched, Etched for 40 seconds with 2% nital. Magnified 100X

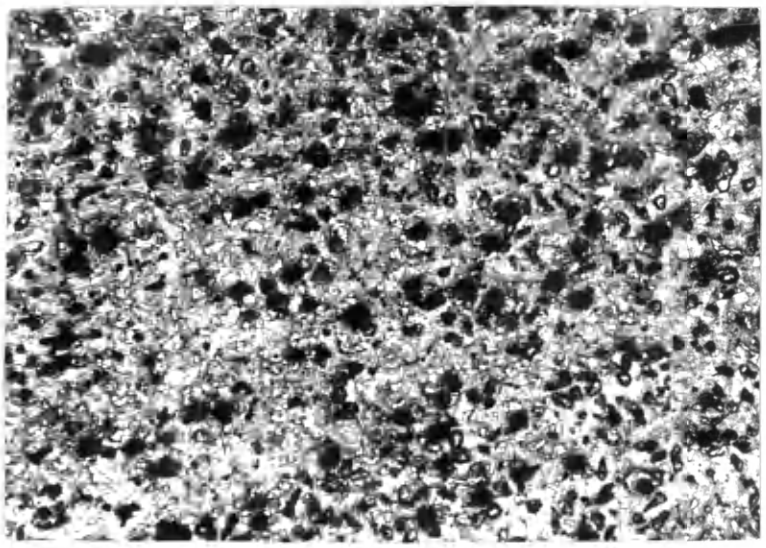


Figure 8. Mg-Si nodular cast iron, Soaked 8 hours at 1800 F, Water quenched, Etched for 20 seconds with 2% nital. Magnified 100X

Figure 9

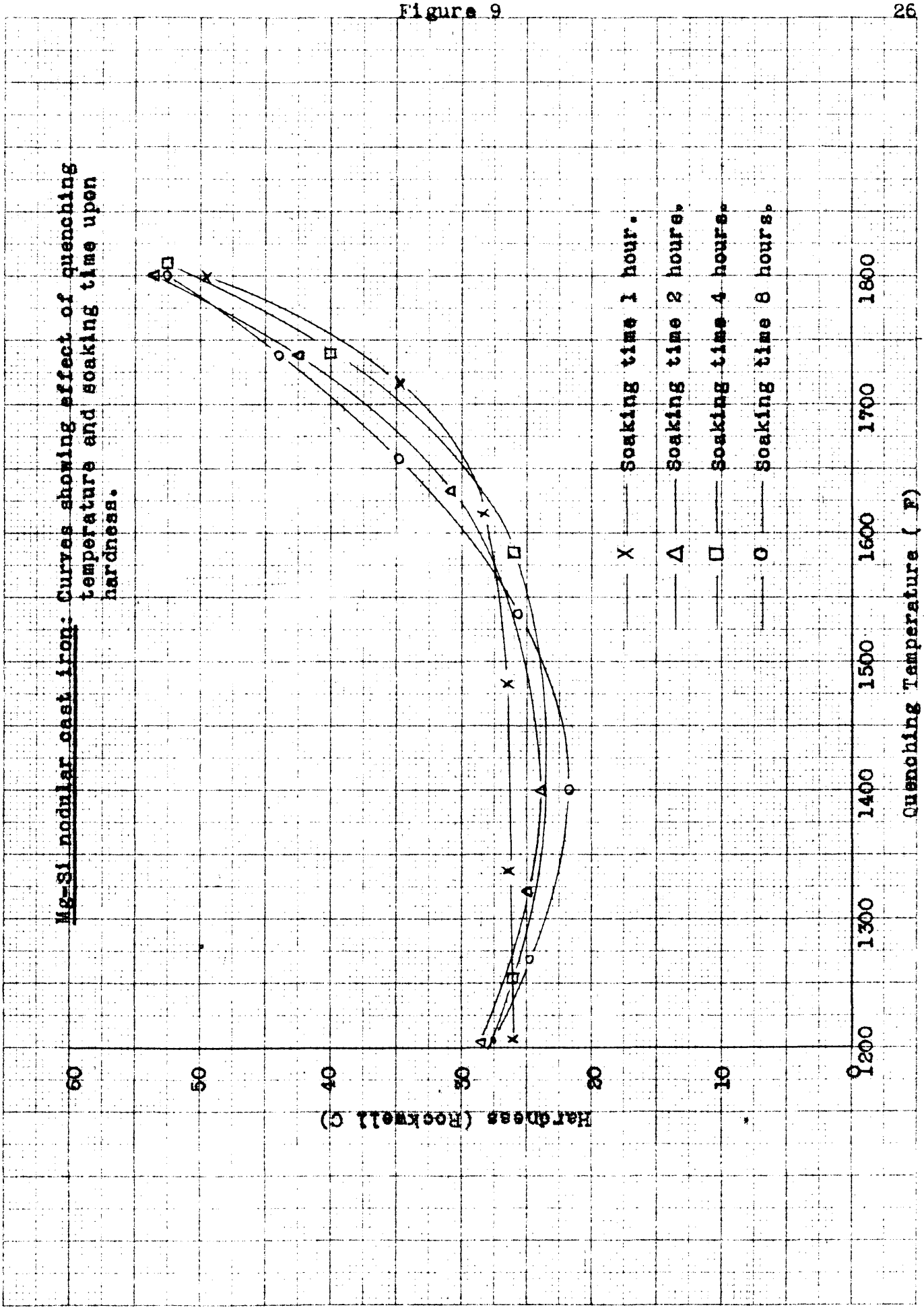

Mg-Si nodular cast iron: Curves showing effect of quenching temperature and soaking time upon hardness.
Hardness (Rockwell C)
60
50
40
30
20
10
0
1200
1300
1400
1500
1600
1700
1800
Quenching Temperature (F)
X — Soaking time 1 hour.
Δ — Soaking time 2 hours.
□ — Soaking time 4 hours.
O — Soaking time 8 hours.

Figure 10

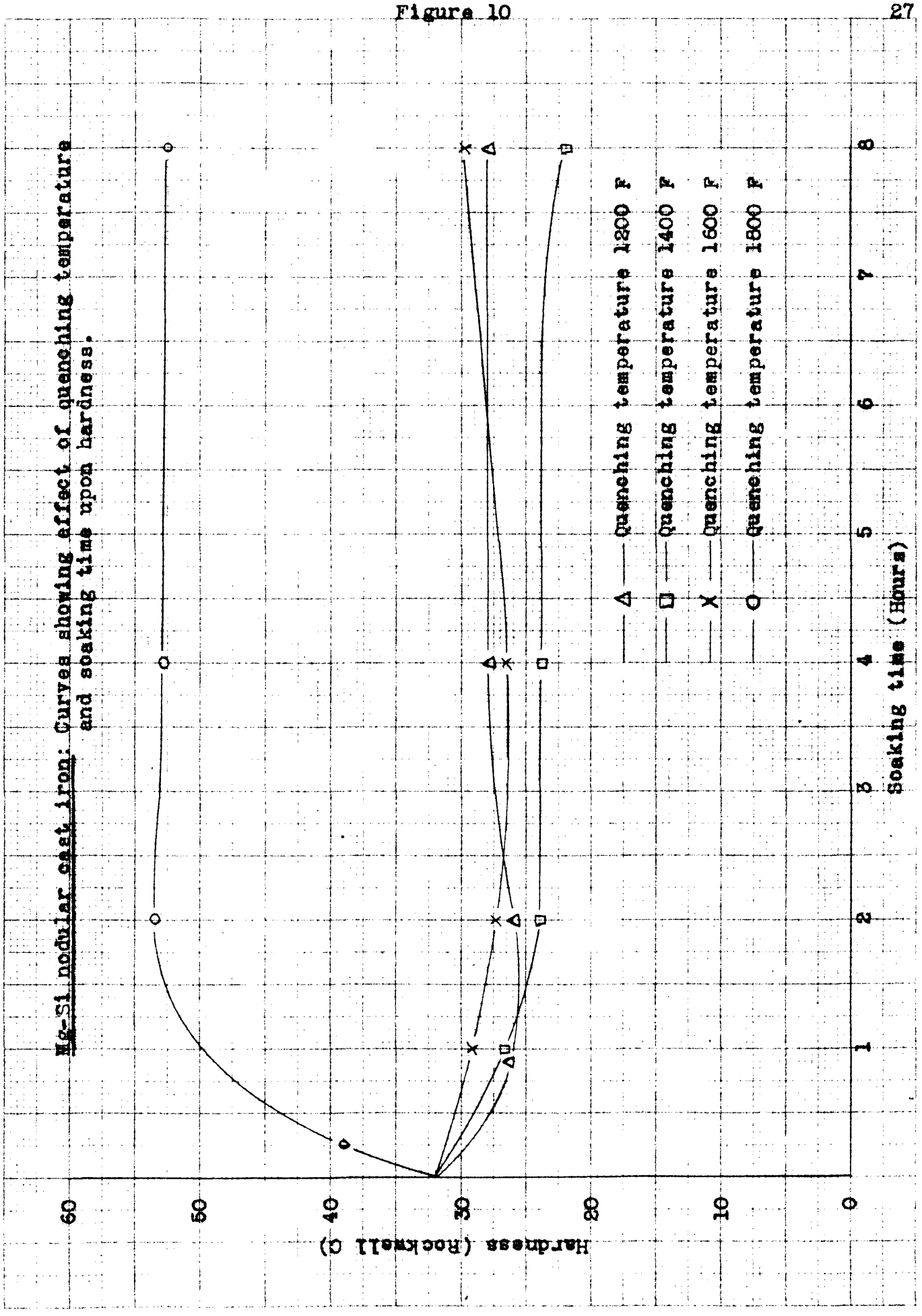
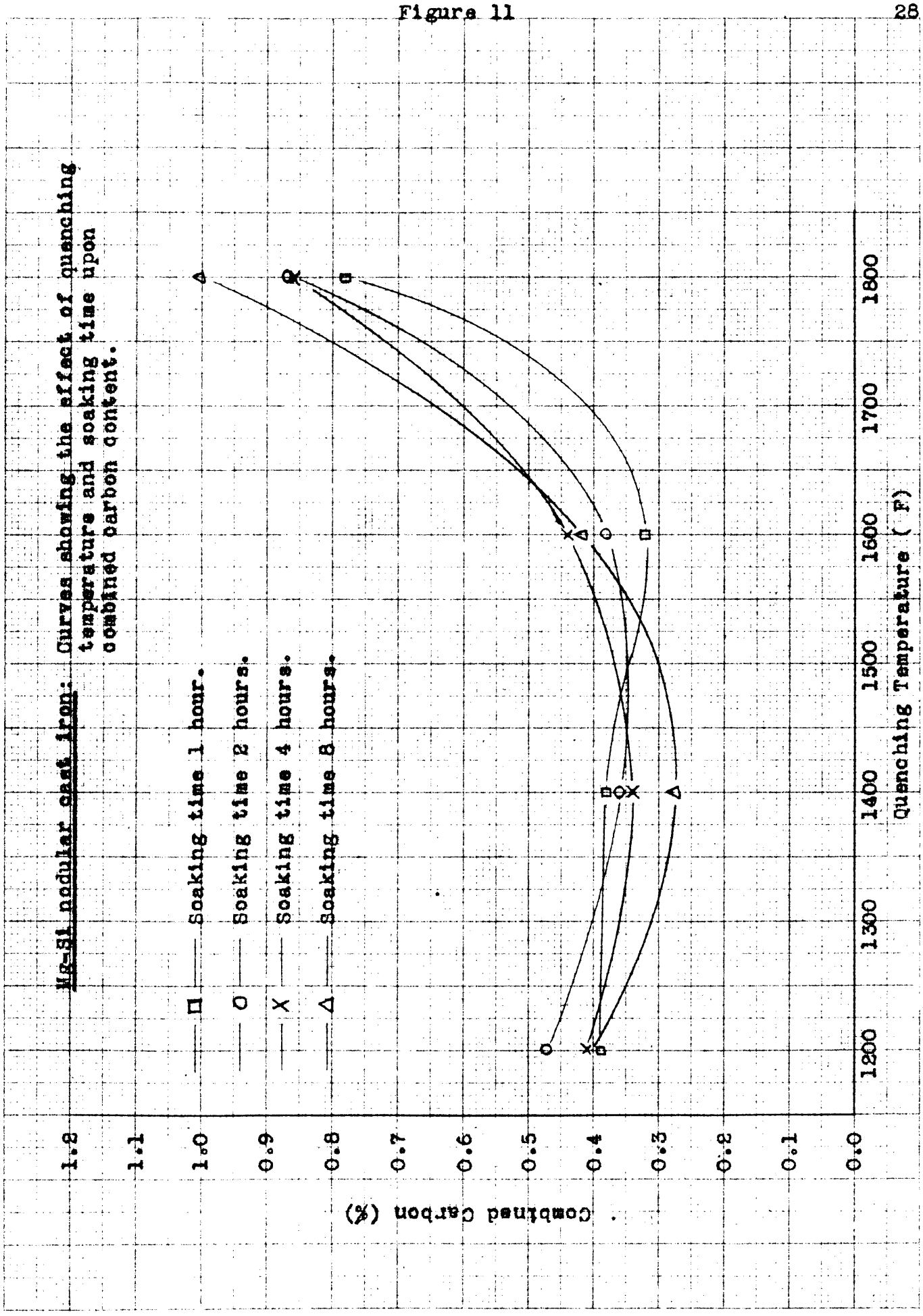

Mg-Si nodular cast iron: Curves showing effect of quenching temperature and soaking time upon hardness.
Hardness (Rockwell C)
Soaking time (Hours)
Quenching temperature 1200 F
Quenching temperature 1400 F
Quenching temperature 1600 F
Quenching temperature 1800 F
0
10
20
30
40
50
60
1
2
3
4
5
6
7
8

Figure 11



MG-81 nodular cast iron: Curves showing the effect of quenching temperature and soaking time upon combined carbon content.

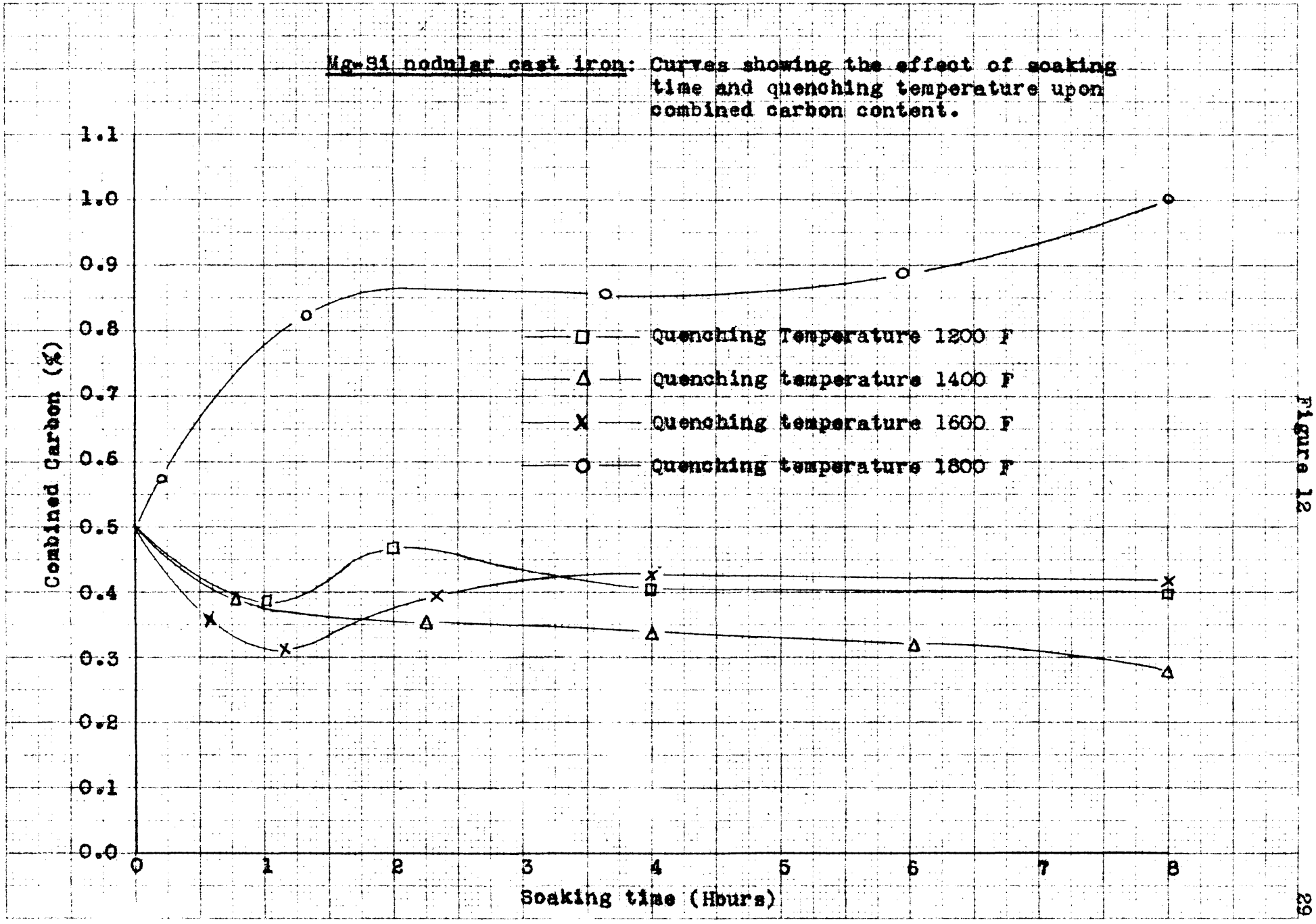

Mg-Si nodular cast iron: Curves showing the effect of soaking time and quenching temperature upon combined carbon content.
Quenching Temperature 1200 F
Quenching temperature 1400 F
Quenching temperature 1600 F
Quenching temperature 1800 F
Combined Carbon (%)
Soaking time (Hours)
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
1
2
3
4
5
6
7
8

Figure 12

EXPERIMENTS USING A NODULAR IRON PREPARED BY USING A Mg-Ni NODULIZING COMPOUND

Introduction

The second phase of this experimental work was conducted using samples of nodular cast iron previously obtained from the International Nickel Company. This iron was prepared by their patented process which involves the use of a Mg-Ni alloy as the nodulizing agent. The analysis of this iron as furnished by the International Nickel Company was: T.C. 3.47%, Si 3.41%, Mn 0.34%, P 0.044%, and Ni 0.94%.

Heating, Soaking, and Quenching

Specimens of Mg-Ni nodular cast iron were heated, soaked, and quenched in the manner previously described (p. 4) under Experimental Procedures.

Hardness Measurements

After specimens were quenched, hardness readings were taken. Table 3 (pp. 37-38) gives the tabulated experimental hardness readings obtained. From this data, curves (Figs. 19-20, pp. 43-44) were plotted.

Carbon Analyses

Each specimen, after quenching, was analyzed for graphitic carbon. The as-cast specimen was also analyzed for total carbon. The combined carbon content of each specimen was then obtained as the difference between total carbon and graphitic carbon. The experimental results obtained are shown in Table 4 (p. 39). From the data in Table 4, curves

(Figs. 21-22, pp. 45-46) were plotted.

Microstructure Examinations

Figure 13 (p. 40) shows the microstructure of the Mg-Ni nodular cast iron in the as-cast, unetched condition. In it may be seen graphite nodules which vary in size from very small to ASTM grain size 5.

Figure 14 (p. 40) shows the microstructure of the iron in the as-cast condition after etching for 40 seconds with 2% nital. In this photomicrograph, you can see areas of dark etching pearlite, gray etching graphite nodules up to ASTM grain size 6 in size, and numerous, very small, dark etching graphite nodules in a matrix of light etching ferrite. The average size of the larger light-etching graphite nodules is about ASTM grain size 6.

Figure 15 (p. 41) shows the microstructure of the Mg-Ni nodular iron after soaking for 8 hours at 1200 F. From this photomicrograph, it may be seen that most of the very small graphite nodules present in the as-cast specimen have disappeared. The appearance of the larger nodules also indicates that some secondary graphite deposition has taken place around the outer edges. This accounts for the disappearance of the very small nodules. Several areas of pearlite are still visible, and the matrix is ferritic.

Figure 16 (p. 41) shows the microstructure after soaking at 1400 F for 8 hours. This photomicrograph shows that most of the pearlite which was present in the as-cast specimen has broken down into ferrite and spheroidized cementite. The

cementite in turn is decomposing into ferrite and small graphite nodules. Secondary deposition of graphite is still taking place, and the matrix is approaching the completely ferritic state. The average size of the larger nodules is about ASTM grain size 6.

Figure 17 (p. 42) shows the microstructure after soaking at 1600 F for 8 hours. This photomicrograph shows that the matrix of the specimen is entirely martensitic and that most of the very small nodules which were visible at lower temperatures have now gone into solution in the previously ferritic matrix. The ferrite has been heated over the critical temperature and has been transformed to austenite then quenched to martensite. The average size of most of the nodules remaining is approximately ASTM grain size 6. This specimen cracked when it was quenched in cold water.

Figure 18 (p. 42) shows the specimen microstructure after soaking for 8 hours at 1800 F. In this photomicrograph you can see a matrix of gray etching martensite in which are found many small to medium size areas of light etching retained austenite and dark etching graphite nodules. The average nodule size has decreased to ASTM grain size 8. This specimen also cracked when quenched in cold water.

DISCUSSION OF EXPERIMENTAL RESULTS

Effect of Quenching Temperature Upon Hardness

From the experimental results shown in Table 3 (pp. 37-38) and the curves drawn from these results (Figs. 19-20, pp. 43-44), it can be seen that the hardness of this iron begins to decrease after soaking for only 1 hour at 1200 F. This slow decrease in hardness at 1200 F continues as the period of exposure to the temperature is lengthened. Part of this decrease in hardness can be attributed to the relief of any residual stresses which may have existed in the iron as-cast, but the major portion of the decrease in hardness is due to the breakdown of carbides in the structure of the iron.

At a quenching temperature of 1400 F, the decrease in hardness of the iron is even more rapid and more complete than at 1200 F. The decrease in hardness at 1200 F and 1400 F in this iron can be easily explained if reference is made to the chemical composition of the iron. It has a very high Si content (3.41%) and also contains 0.94% Ni. Nickel in cast irons has the action of a graphitizer and, like silicon, assists in carbide decomposition [9]. In addition to reducing and eliminating free carbide, nickel reduces pearlitic combined carbon mildly, particularly up to about 1.5% nickel.

At quenching temperatures of 1600 F and 1800 F, this particular nodular iron has apparently passed its critical temperature and transformed to austenite. The combined carbon content begins to get higher and upon quenching martensitic

structures are obtained. As the percentage of carbon dissolved in the austenite gets higher, we finally begin to obtain retained austenite in the specimen.

Effect of Soaking Time Upon Hardness

With this particular nodular iron, the effect of longer soaking periods appeared to be merely a continuation of whatever result was observed with a short soaking period. For example, if the iron exhibited a tendency to soften after soaking for 1 hour this softening was continued when the soaking time was increased to 8 hours. This effect was observed at all temperatures except 1800 F. At a soaking temperature of 1800 F, the hardness of the specimens began to decrease when soaking times over 1 hour were used. This decrease in hardness at this temperature was accompanied by increased solution of carbon, which in turn allowed for more and more retained austenite in the quenched specimens. This greater and greater percentage of retained austenite accounts for the decreasing hardness at longer soaking times.

It is felt that in the case of specimens which were soaked at 1200 F and 1400 F the hardness values would have eventually reached constant figures if the soaking times had been increased to 16 or 24 hours.

Effect of Quenching Temperature Upon Microstructure

Evidence of changes in microstructure brought about by higher and higher quenching temperatures is given in Figures 13-18 (pp. 40-42). These photomicrographs show visually the changes that take place in a Mg-Ni nodular cast iron after

soaking for the same length of time at different quenching temperatures. They give visual evidence of the breakdown of pearlite and carbides at temperatures of 1200 F and 1400 F as a result of the graphitizing action of silicon and nickel. In Figures 17-18 (p. 42), the photomicrographs show the effect of increased amounts of dissolved carbon upon the internal structure of ferrous alloys.

Effect of Soaking Time Upon Microstructure

Examination of the microstructure of all heat-treated specimens showed that structural changes in the various specimens are a direct function of the quenching temperature, and that these changes move toward completion - which implies a move toward constituents which are stable at that temperature - as longer and longer soaking periods at that temperature are allowed. This observation holds true for all specimens of this particular Mg-Ni nodular iron regardless of quenching temperature or soaking time.

Effect of Quenching Temperature Upon Combined Carbon Content

At quenching temperatures of 1200 F and 1400 F, the combined carbon content of the specimens steadily decreased as soaking times were increased from 1 to 8 hours. This decrease in combined carbon content is accounted for by the graphitizing action of the silicon and nickel in the iron which causes the carbides present to break down into ferrite and graphite. Rehder, in his work on the annealing of nodular cast irons [10], has shown that the breakdown of pearlite

proceeds rapidly at first; but the final traces of pearlite are extremely hard to remove, especially in nodular irons made by the use of some nodulizing agent containing magnesium.

At the higher quenching temperatures of 1600 F and 1800 F, the combined carbon content of all samples increased as soaking periods were lengthened. This seems to agree with expected results, so no further discussion is required.

Table 3 Hardness Readings

Mg-Ni nodular cast iron: Effect of Quenching Temperature and Soaking Time Upon Hardness.

Specimen condition	Hardness (Rockwell C) at different points on the specimen.	Average Hardness
As cast	17.3, 13.8, 17.5, 12.6, 14.9, 15.7, 16.4, 11.8, 13.7	14.8
Soaked at 1200 F for 1 hour	10.3, 12.5, 15.1, 16.4, 13.3, 15.4, 14.3, 14.8, 13.4	13.9
Soaked at 1200 F for 2 hours	9.0, 13.8, 14.5, 14.5, 15.2, 13.8, 13.3, 11.5, 6.0	12.4
Soaked at 1200 F for 4 hours	9.0, 10.6, 12.8, 14.5, 13.8, 14.5, 14.2, 12.8, 11.5	12.6
Soaked at 1200 F for 8 hours	7.1, 11.1, 10.8, 11.1, 9.8, 11.8, 13.0, 10.4, 10.4	10.6
Soaked at 1400 F for 1 hour	11.3, 12.1, 12.2, 12.7, 13.6, 13.3, 12.7, 12.9, 12.4	12.6
Soaked at 1400 F for 2 hours	12.0, 10.6, 11.0, 9.9, 7.8, 11.5, 12.0, 11.2, 8.3	10.3
Soaked at 1400 F for 4 hours	5.5, 9.6, 11.8, 11.0, 10.3, 10.3, 8.8, 9.6, 8.5	9.5
Soaked at 1400 F for 8 hours	6.6, 7.6, 7.3, 9.1, 7.7, 11.0, 9.4, 7.3, 4.9	7.9

Table 3 Hardness Readings (continued)

Mg-Ni nodular cast iron: Effect of Quenching Temperature and Soaking Time Upon Hardness.

Specimen condition	Hardness (Rockwell C) at different points on the specimen.	Average Hardness
Soaked at 1600 F for 1 hour	53.1, 51.0, 56.9, 55.3, 54.3, 53.5, 54.5, 55.1, 54.6	54.3
Soaked at 1600 F for 2 hours	56.4, 53.5, 52.6, 55.0, 51.0, 53.0, 54.0, 56.0, 56.8	54.3
Soaked at 1600 F for 4 hours	54.4, 54.7, 54.4, 54.6, 53.3, 54.8, 53.8, 54.7, 54.3	54.3
Soaked at 1600 F for 8 hours	55.0, 51.0, 54.5, 54.3, 53.1, 54.3, 54.7, 56.8, 55.4	54.3
Soaked at 1800 F for 1 hour	55.3, 54.9, 53.0, 55.4, 54.4, 55.9, 55.5, 55.0, 53.2	54.7
Soaked at 1800 F for 2 hours	51.8, 52.3, 51.0, 51.5, 48.8, 50.0, 49.8, 50.3, 52.0	50.8
Soaked at 1800 F for 4 hours	48.0, 47.9, 50.8, 50.4, 49.2, 48.5, 47.5, 48.0, 46.0	48.5
Soaked at 1800 F for 8 hours	51.8, 52.7, 33.0, 20.5, 48.6, 47.6, 33.0, 38.0, 32.5	39.7

Table 4 Carbon Analyses

Mg-Ni nodular cast iron: Table showing combined carbon content of specimens after soaking at different temperatures for varying periods of time.

Specimen	Quenching Temp. (F)	Soaking Time (Hrs)	T.C. (%)	G.C. (%)	C.C. (%)
10 (As cast)			3.47	3.22	0.25
10G	1200	1	3.47	3.26	0.21
10H	1200	2	3.47	3.30	0.17
10I	1200	4	3.47	3.29	0.18
10J	1200	8	3.47	3.34	0.13
10A	1400	1	3.47	3.32	0.15
10K	1400	2	3.47	3.34	0.13
10L	1400	4	3.47	3.37	0.10
10B	1400	8	3.47	3.39	0.08
10E	1600	1	3.47	2.67	0.80
10M	1600	2	3.47	2.65	0.82
10N	1600	4	3.47	2.60	0.87
10F	1600	8	3.47	2.59	0.88
10C	1800	1	3.47	2.67	0.80
10O	1800	2	3.47	2.55	0.92
10P	1800	4	3.47	2.38	1.09
10D	1800	8	3.47	2.03	1.44

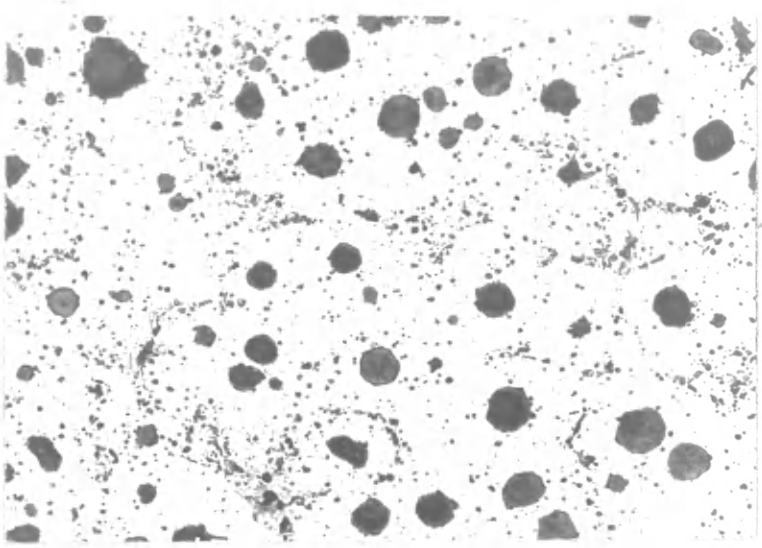


Figure 13. Mg-Ni nodular cast iron,
As cast, Unetched, Magnified 100X

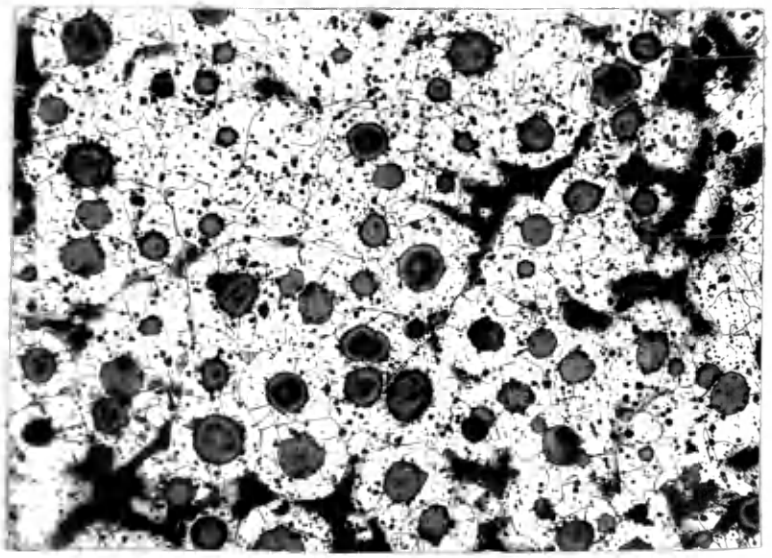


Figure 14. Mg-Ni nodular cast iron,
As cast, Etched for 40 seconds
with 2% nital. Magnified 100X

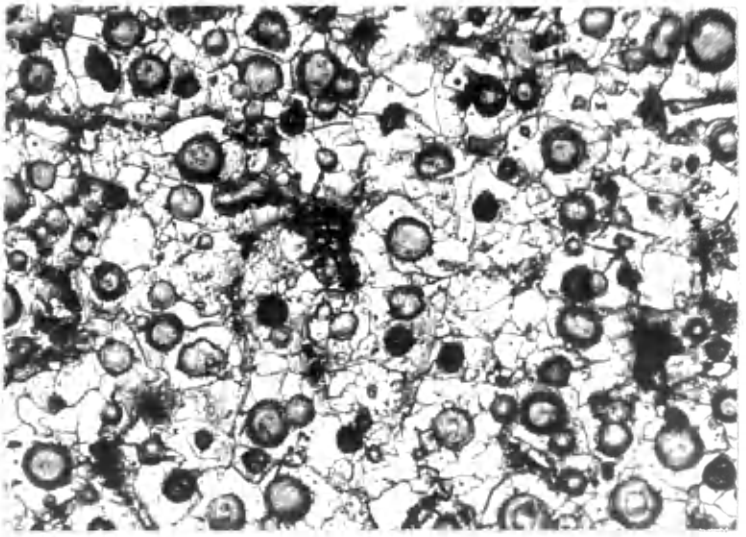


Figure 15. Mg-Ni nodular cast iron, Soaked at 1200 F for 8 hours, Water quenched, Etched 40 seconds with 2% nital. Magnified 100X

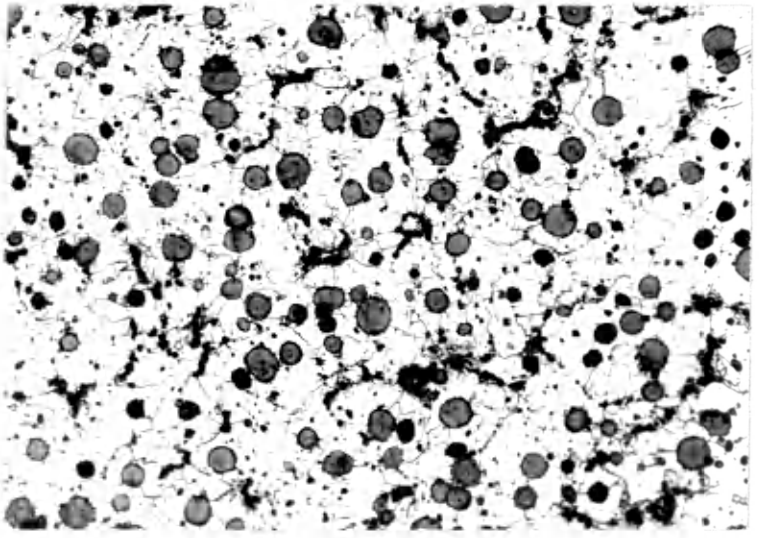


Figure 16. Mg-Ni nodular cast iron, Soaked at 1400 F for 8 hours, Water quenched, Etched 40 seconds with 2% nital. Magnified 100X

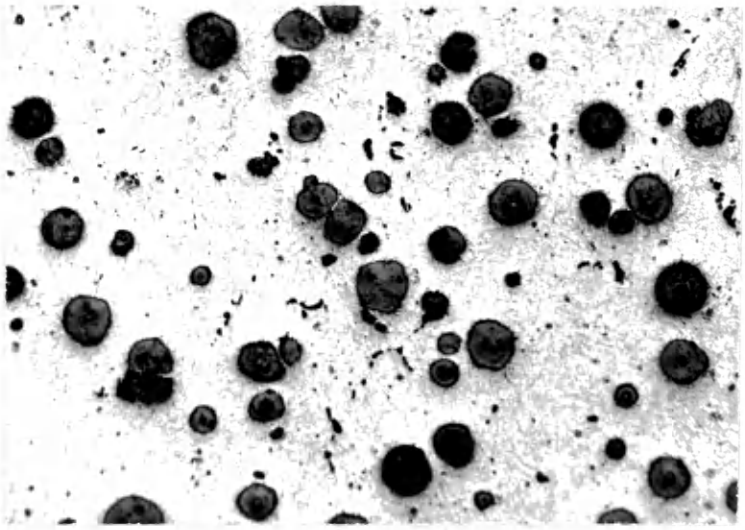


Figure 17. Mg-Ni nodular cast iron, Soaked at 1600 F for 8 hours, Water quenched, Etched 40 seconds with 2% nital. Magnified 100X

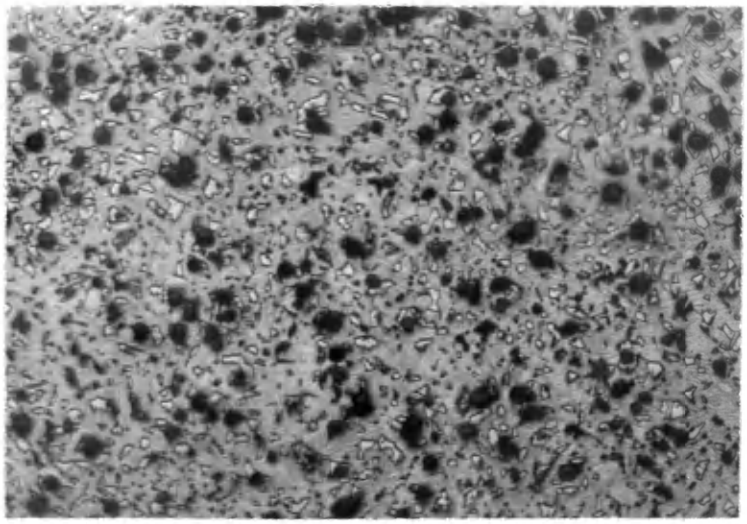
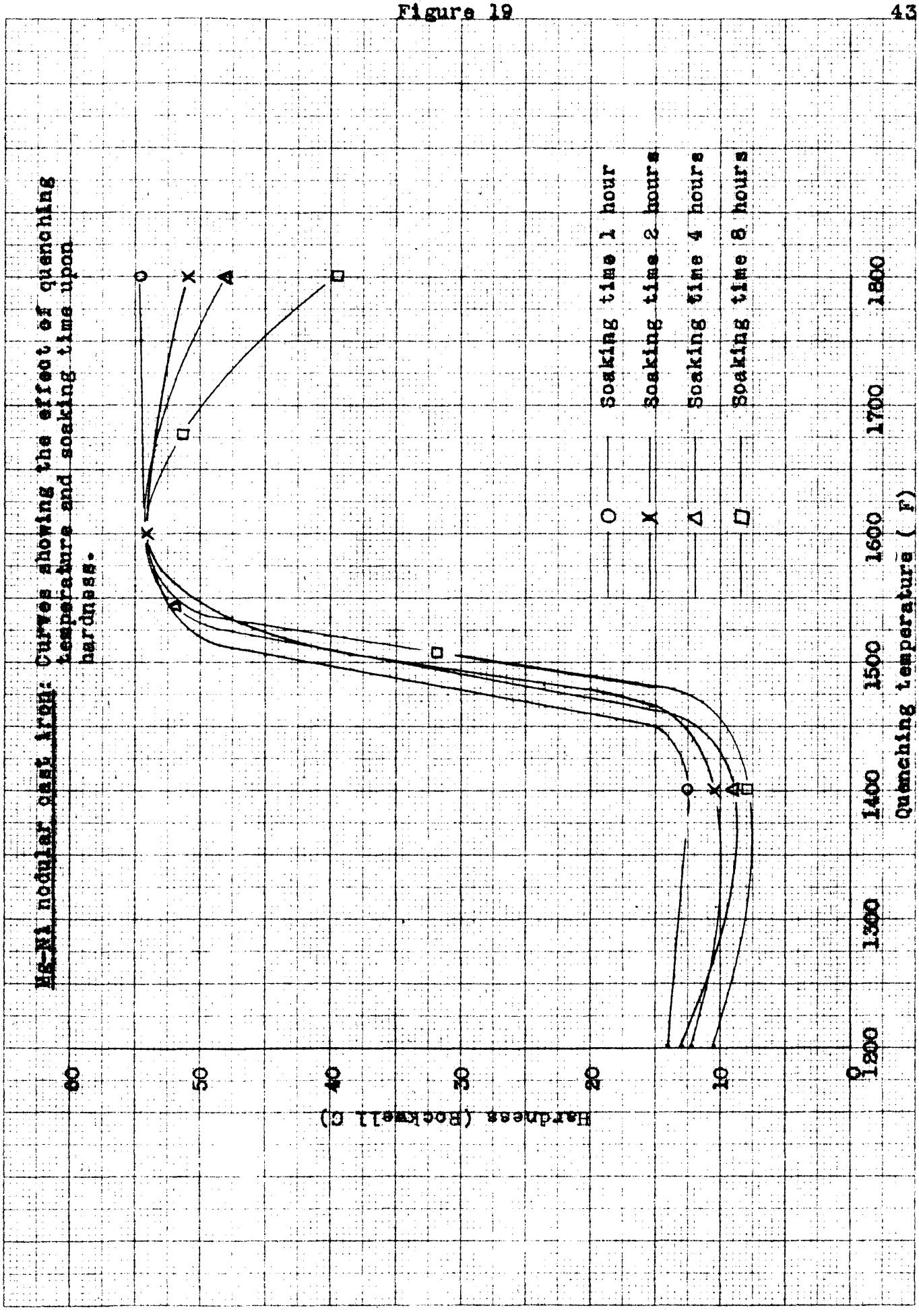
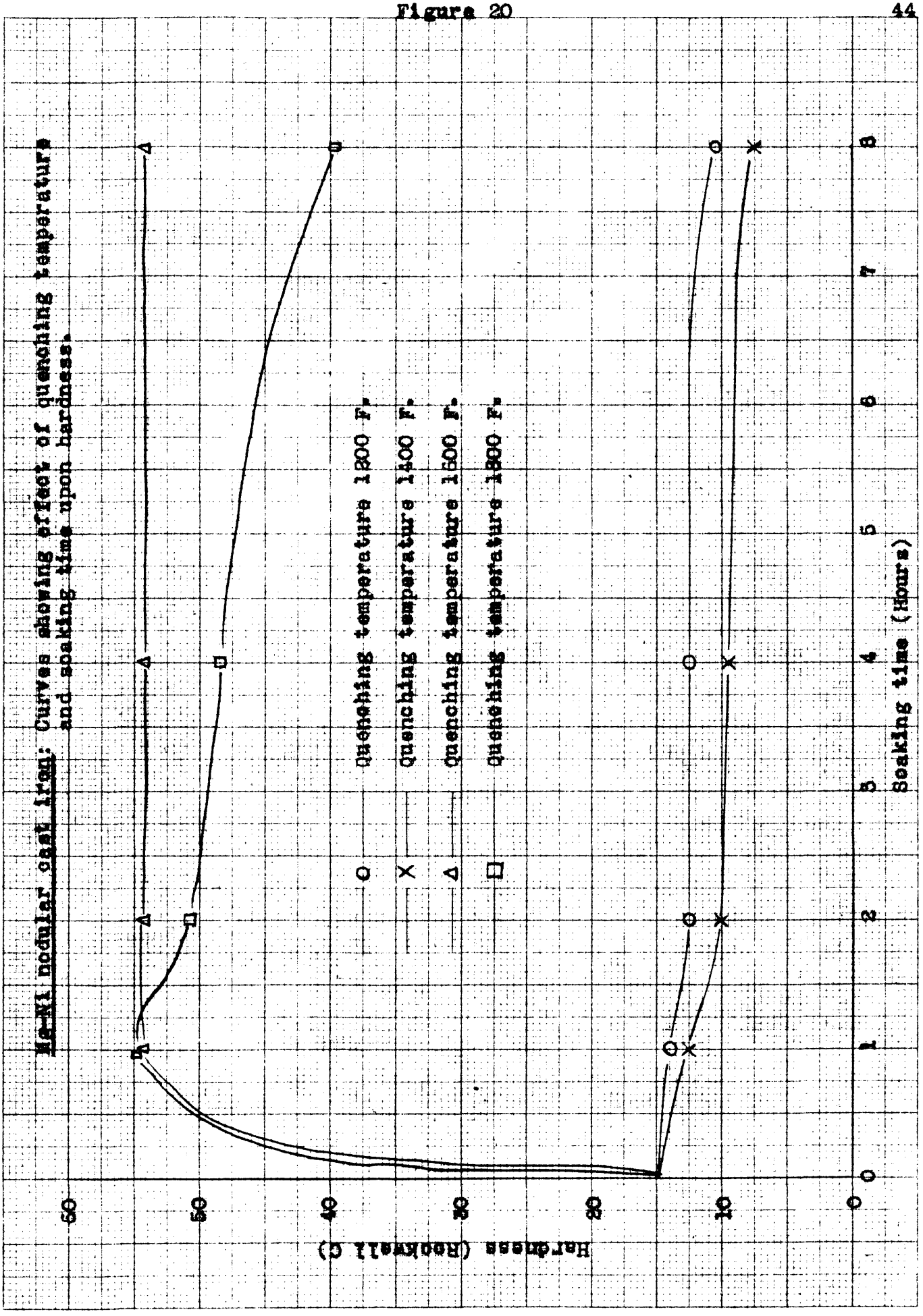


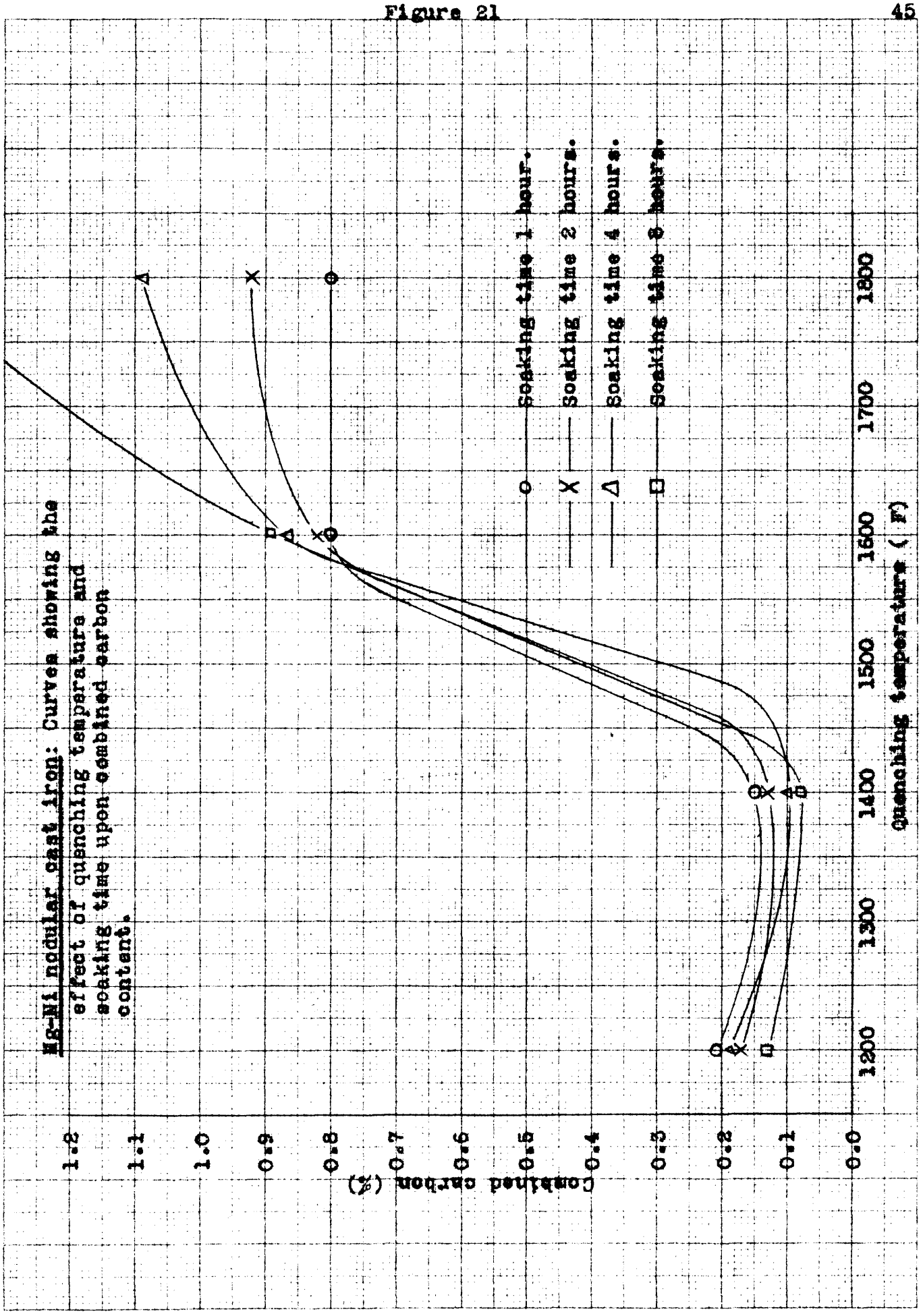
Figure 18. Mg-Ni nodular cast iron, Soaked at 1800 F for 8 hours, Water quenched, Etched 20 seconds with 2% nital. Magnified 100X



Ni-Mi nodular cast iron: Curves showing the effect of quenching temperature and soaking time upon hardness.

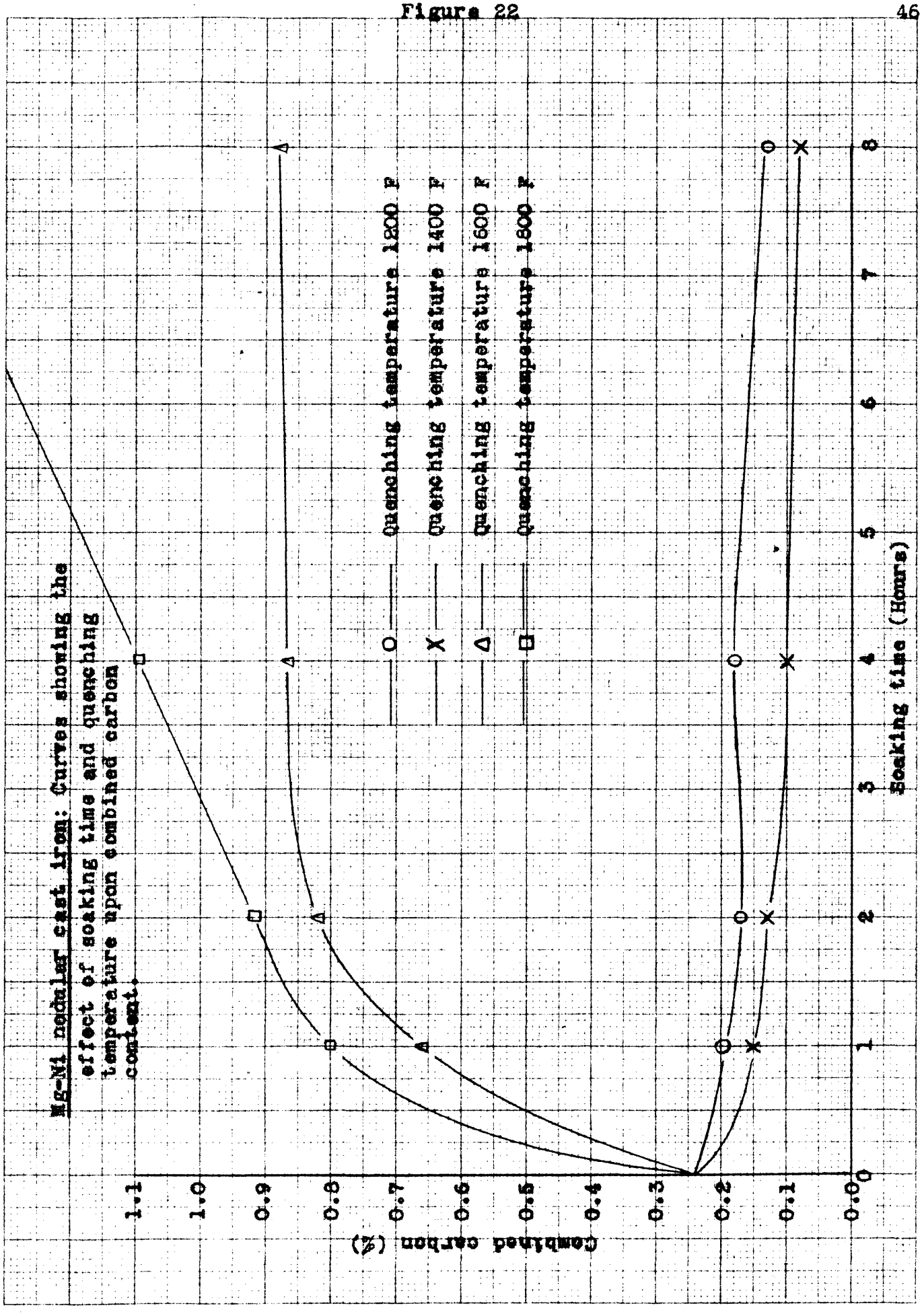
Figure 20


Ni-Mi nodular cast iron: Curves showing effect of quenching temperature and soaking time upon hardness.
Quenching temperature 1200 F.
Quenching temperature 1400 F.
Quenching temperature 1500 F.
Quenching temperature 1600 F.
Hardness (Brookwall C)
Soaking time (Hours)
60
50
40
30
20
10
0
1
2
3
4
5
6
7
8



Mg-Ni nodular cast iron: Curves showing the effect of quenching temperature and soaking time upon combined carbon content.

Figure 22



Mg-Ni nodular cast iron: Curves showing the effect of soaking time and quenching temperature upon combined carbon content.

EXPERIMENTS ON HEAT TREATING A NODULAR IRON

Introduction

Although most nodular irons in the as-cast condition reportedly have tensile strengths and ductility not ordinarily found in gray cast irons, a general statement to this effect cannot be made unless it is somewhat modified. For example, under certain casting conditions and with certain compositions of iron, an entirely ferritic matrix might be encountered in some nodular irons while under other conditions the matrix might be almost entirely pearlitic in nature. In certain other cases, the matrix might be martensitic, or it might even contain retained austenite in extreme cases. Under most normal casting conditions, however, the only types of matrices which would commonly be encountered in nodular irons are entirely ferritic, entirely pearlitic, or combinations of ferrite and pearlite which lie somewhere between these two extremes. It may easily be seen then that it might be possible to have nodular irons in the as-cast condition which would have greater ductility than gray irons but at the same time not have as great a tensile strength. The case where the nodular iron might have the greatest tensile strength is also entirely possible.

In most normal cases with nodular iron, the matrix is predominantly pearlite; and the heat-treating cycle desired is one whereby the existing pearlite and carbides in the iron will be as completely as possible decomposed so we

will obtain improved ductility, resistance to impact, and better machinability even at the expense of lowered tensile strengths. With the fewer cases where the matrix is ferritic, however, we desire to establish suitable heat-treating cycles to increase the strength of the iron by causing more pearlite and carbides to appear in the matrix. It is realized that by using such a heat-treating cycle we decrease ductility, decrease resistance to impact, and increase resistance to machining. Many products in which nodular iron may be used require higher strengths than those furnished by purely ferritic irons; therefore it is necessary to sacrifice these properties somewhat in order to secure the higher strengths associated with a pearlitic matrix.

The nodular iron used in this final phase of the work was one furnished by the International Nickel Company. It had an almost completely ferritic matrix. With this type of matrix, nodular iron does not exhibit its greatest strength properties; therefore the problem to be faced is that of determining suitable heat-treating cycles whereby the strength of the iron might be raised to higher levels. The analysis of this iron was exactly the same as given previously (p. 30). Since it contains 0.94% Ni, it must be considered as an alloy cast iron. This is a situation which will be encountered frequently, however, since one of the principal nodulizing agents in use at the present time is a Mg-Ni alloy.

The principal objects of this final phase of work are:

(1) to determine some suitable heat-treating cycles for nodular irons which are largely ferritic in the as-cast condition, and (2) to determine the effect of these heat-treatments upon the mechanical properties of the iron.

EXPERIMENTAL METHODS AND EQUIPMENT USED

Preparation of Tensile Specimens

Several months previous to the undertaking of this work, the Department of Metallurgy received from the International Nickel Company a number of specimens of nodular cast iron which were of a size suitable for use as tensile specimens. These specimens, as furnished, were 8-inches in length and of 1-inch square stock. From these square bars, tensile specimens with a diameter of .8-inch and with a machined length suitable for use with a 2-inch gauge length were machined. A total of six of these specimens was furnished for this phase of the work.

Determination of Heat-Treating Temperature

Since there were only a few specimens available for tensile tests, it was decided that prior to actual heat-treatment of the specimens it would be desirable to determine a suitable temperature at which the specimens could be soaked in order to attain the desired solution of carbon in the matrix within a reasonable length of time. This temperature was determined by using several smaller samples which were available. These smaller samples were each soaked for a period of 45 minutes, but the temperature of soaking for each sample was varied. One sample was soaked at 1500 F, one at 1550 F, one at 1600 F, one at 1650 F, and one at 1700 F. After soaking at these temperatures for 45 minutes, the samples were removed from the furnace, covered with foundry sand, and allowed to cool to room temperature. After cooling,

each specimen was polished, etched, and examined microscopically. By this means, it was determined that a specimen of this iron which had been soaked at 1650 F for 45 minutes and allowed to cool slowly while covered with foundry sand would have a completely pearlitic matrix. It was felt that this type of matrix would be an ideal one from which much higher tensile strengths could be expected. This particular austenitizing temperature was therefore selected and used.

Selection of Actual Heat-Treating Cycle

After selection of the temperature at which the specimens would be heat-treated, there remained the problem of deciding upon the actual heat-treating cycle to be used. Since there were so few tensile specimens available and it was not desired to break them all in the same heat-treated condition, it was decided that two of the specimens would be broken in the as-cast condition, two more would be broken after heat-treating and slow cooling, and that the last two would be broken after heat-treating, oil quenching, and tempering for 3 hours at 1000 F. By the selection of such cycles, it was felt that in the second case the tensile strength of the iron could be raised to high values while the ductility and elongation remained low, and in the third case the tensile strength would also be high while the ductility and the elongation would be improved over the slow-cooled iron.

Heat Treatment of the Specimens

Actual heat-treating of the iron specimens was carried out in an electric, resistance-type furnace equipped with an indicating thermometer and automatic temperature control. The specimens were all exposed to the furnace atmosphere while heating and soaking. All specimens were placed in the furnace before it was turned on and were brought to temperature with the furnace. Timing of the soaking period was begun as soon as the indicating thermometer reached the desired temperature. As soon as the desired soaking period had elapsed, two of the specimens were removed from the furnace, buried in a bucket of foundry sand, and allowed to cool to room temperature. The other two specimens were removed from the furnace, quenched in oil, and tempered at 1000 F for 3 hours. The two tempered specimens were then allowed to cool in air to room temperature.

Hardness Measurements

Prior to and after all heat-treatments, the hardness of all specimens was taken on a standard Brinell hardness testing machine.

Tensile Tests

The actual testing of all tensile specimens was conducted on a hydraulic, 120,000-pound capacity, Tinius Olsen testing machine. Except in the case of the as-cast specimens, SR-4 strain gauges were mounted on each specimen; and strain measurements were made by means of a Baldwin SR-4 strain indicator. The tensile load was applied to each specimen

at the rate of 2000 pounds per minute, and strain readings were taken after each 2000-pound increment of load had been applied.

Elongation Measurements

Prior to breaking, the machined section of each tensile specimen was marked with a 2-inch gauge length. After each specimen had been broken, the increase in length between these two marks was measured in order to determine the amount of permanent deformation which had taken place in the specimen.

EXPERIMENTAL RESULTS OBTAINED

Changes in Hardness due to Heat Treatment

Changes in the Brinell hardness of tensile specimens due to the various heat-treatments used are tabulated in Table 5 (p. 59).

Changes in Tensile Strength due to Heat Treatment

Two tensile specimens were broken in the as-cast condition. One of these specimens failed under a tensile load of 38,000 pounds per square inch, and the second failed under a load of 43,000 pounds per square inch. Neither of these figures is considered to be satisfactorily representative of the strength of this iron since both tensile specimens showed sizable slag inclusions in the fracture area. These slag inclusions undoubtedly lowered the tensile strength of the iron considerably. In both cases, the fractures were brittle type. The tensile loads under which the six specimens broke were:

As cast	38,000 psi
As cast	43,000 psi
Heat-treated, slow-cooled	53,500 psi
Heat-treated, slow-cooled	52,800 psi
Quenched and tempered	64,800 psi
Quenched and tempered	56,700 psi

It may be seen from the above figures that by heat-treating and slow-cooling this particular nodular iron its tensile strength was raised about 10,000 pounds per square inch. By quenching and tempering the specimens, tensile strengths were raised by several thousand pounds per square inch above those attained by slow cooling. Brittle type fractures were

obtained with all specimens.

Changes in Matrix due to Heat Treatment

The matrix structure of the tensile specimen in the as-cast condition is shown in Figure 14 (p. 40). Matrix structures of the heat-treated specimens are shown in Figures 23-24 (p. 60). The matrix has changed from essentially ferritic in the as-cast condition to pearlitic in the slow-cooled condition and tempered martensite in the case of the quenched-and-tempered specimen.

DISCUSSION OF EXPERIMENTAL RESULTS

Changes in Specimen Hardness

It is a well known fact among ferrous metallurgists that the hardness of ferrous alloys is a function of the percentage of combined carbon in the alloy under consideration. It is also well known that the solubility of carbon in iron increases to a definite maximum value as the temperature of the iron alloy is increased. Kahles and Goldhoff, in their work on annealing of nodular cast irons [11], have shown that with the nodular irons they used the time for complete solution of carbon varied from 1½ to 7 hours depending upon the temperatures used and the chemical composition of the iron. Results obtained in the second phase of this thesis showed that with the same iron which is being used in this phase complete solution of carbon was not attained in 8 hours at a temperature of 1800 F. However, after only 1 hour at 1600 F, the critical temperature had been exceeded and enough carbon dissolved so that purely martensitic structures were obtained upon quenching. This would seem to indicate that with the particular iron being used the solution of carbon is fairly rapid during the early part of the soaking period, especially at temperatures of 1600 F and higher. From these facts, it may be seen that the tensile specimens in question reacted in the manner expected with regard to hardness. The amount of carbon dissolved was apparently considerable since hardnesses of 512 Brinell were obtained in the oil-quenched specimens prior to tempering.

Changes in Specimen Matrix

The different matrices obtained were different only because the specimens were treated differently after the soaking period and not because of different combined carbon content at the time they were removed from the furnace. In the specimens which were slow-cooled in foundry sand, the decrease in temperature was slow enough so that carbon had time to diffuse from the austenite. This resulted in a fine pearlitic decomposition product. This pearlite, in the vicinity of the graphite nodules, then broke down into ferrite and spheroidized cementite. The spheroidized cementite then decomposed into ferrite and graphite, which deposited on the graphite nodules originally present. This sequence of events accounts for the bull's-eye structure seen in the photomicrograph of the slow-cooled specimen.

In the oil-quenched specimen, most of the carbon dissolved in the austenite was trapped there by the rapid cooling and caused the austenite to convert to martensite. Upon tempering, this martensite began to lose carbon by the formation of tiny spheroids of cementite. As a result of this loss of carbon, the tempered martensite structure also decreased in hardness.

Changes in Tensile Strength

Rehder [12] in his work and Kahles and Goldhoff [13] in their work have all shown that tensile strengths of nodular irons may be varied by changing the composition of the matrix of the iron. Results of their work show that irons with a ferritic matrix have the best ductility,

resistance to impact, and are more easily machinable than nodular irons containing pearlite and primary carbides in the matrix. The irons with the highest tensile strengths, however, are those in which these carbidic and pearlitic constituents are present in the matrix. With these facts in mind, we may explain the increases in tensile strength of the heat-treated specimens as being due to increased amounts of combined carbon in the matrix caused by the different heat-treating cycles used upon the various specimens.

Table 5 Hardness (Brinell)

Mg-Ni nodular cast iron: Effect of Heat Treatment Upon Brinell Hardness of Mg-Ni nodular cast iron.

Specimen condition	Hardness (Brinell) at different points on the specimen.	Average Hardness
AS cast	192 196 207 196	198
As cast	207 192 196 192	197
Soaked at 1650 F for 45 minutes, slow cooled.	269 262 269 269	267
Soaked at 1650 F for 45 minutes, slow cooled.	262 269 269 269	267
Soaked at 1650 F for 45 minutes, oil quenched, tempered at 1000 F for 3 hours.	311 321 311 302	311
Soaked at 1650 F for 45 minutes, oil quenched, tempered at 1000 F for 3 hours.	302 311 321 311	311

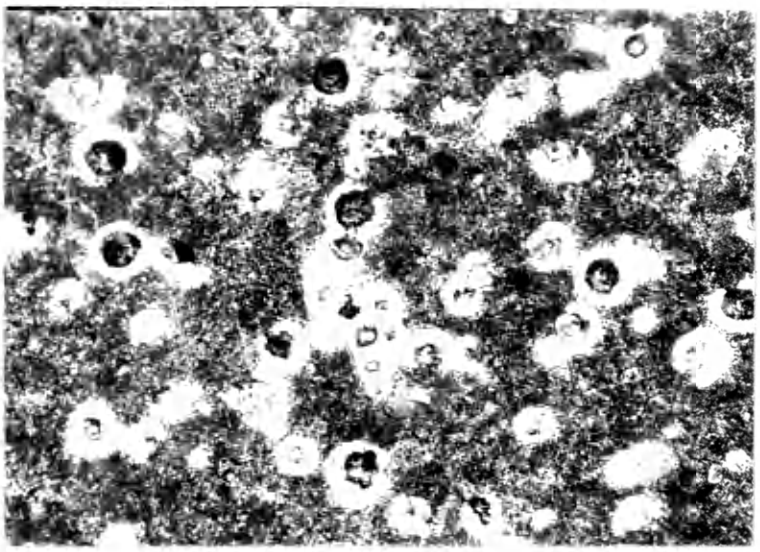


Figure 23 Magnified 100X
Mg-Ni nodular cast iron, Soaked at 1650 F for 45 minutes, Slow cooled in sand, Etched 20 seconds with 2% nital.

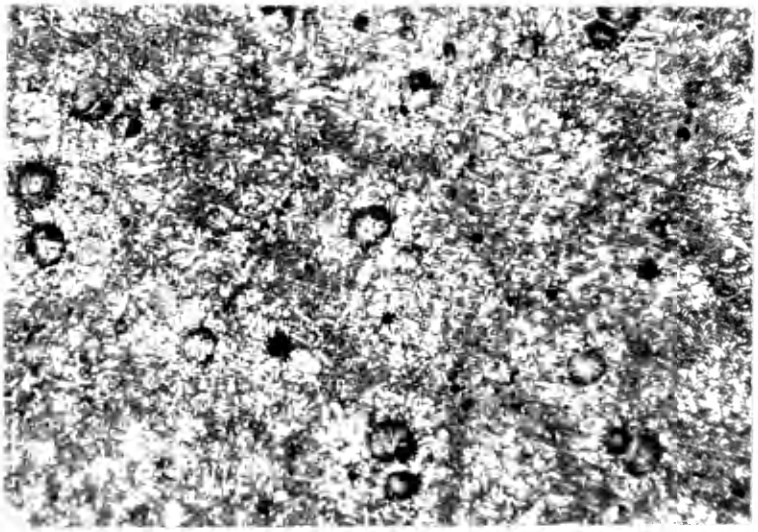


Figure 24 Magnified 100X
Mg-Ni nodular cast iron, Soaked at 1650 F for 45 minutes, oil quenched, tempered at 1000 F for 3 hours, etched 5 seconds with 2% nital.

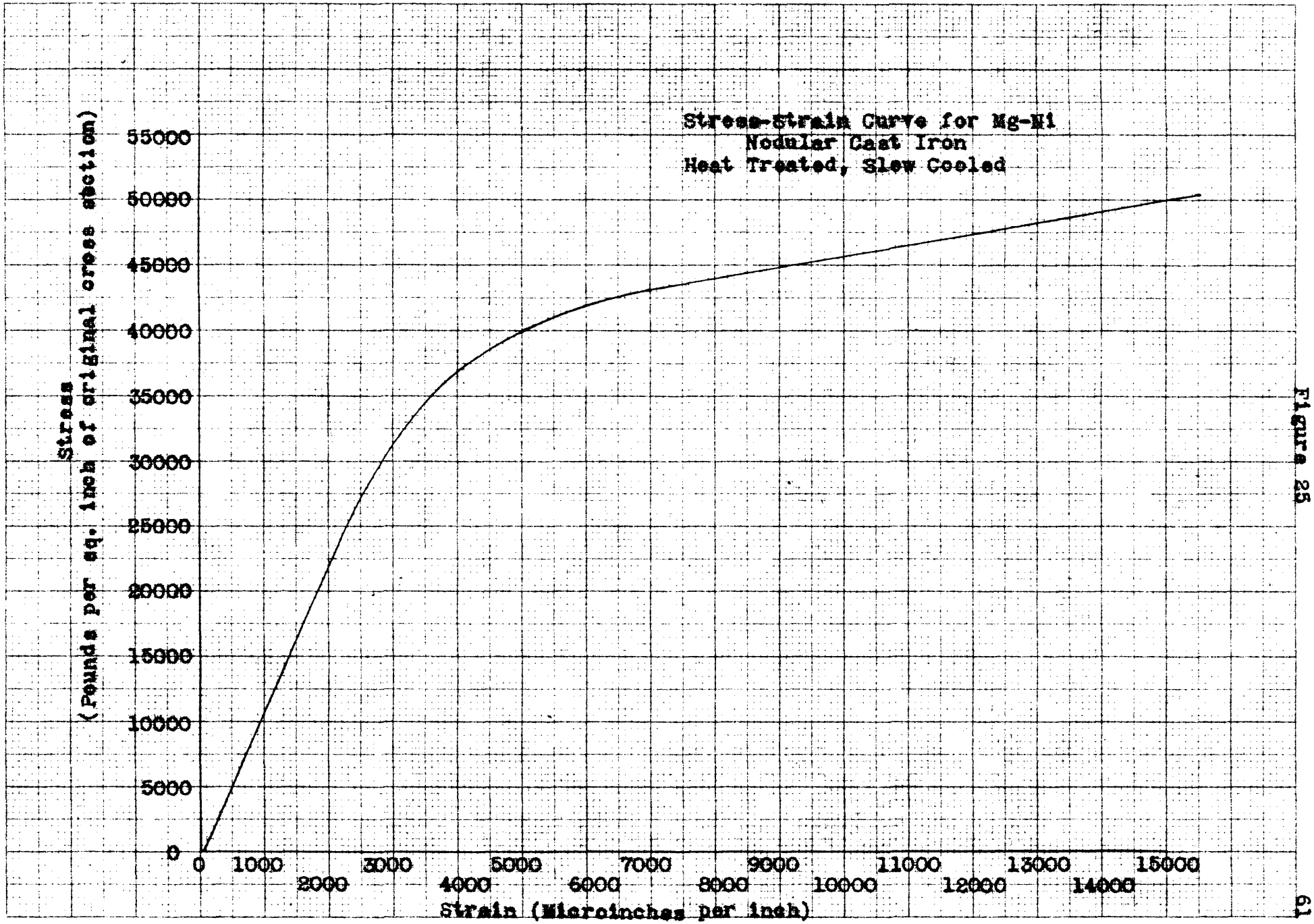

Stress-Strain Curve for Mg-Ni
Nodular Cast Iron
Heat Treated, Slow Cooled
Stress
(Pounds per sq. inch of original cross section)
55000
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
13000
14000
15000
Strain (Microinches per inch)

Figure 25

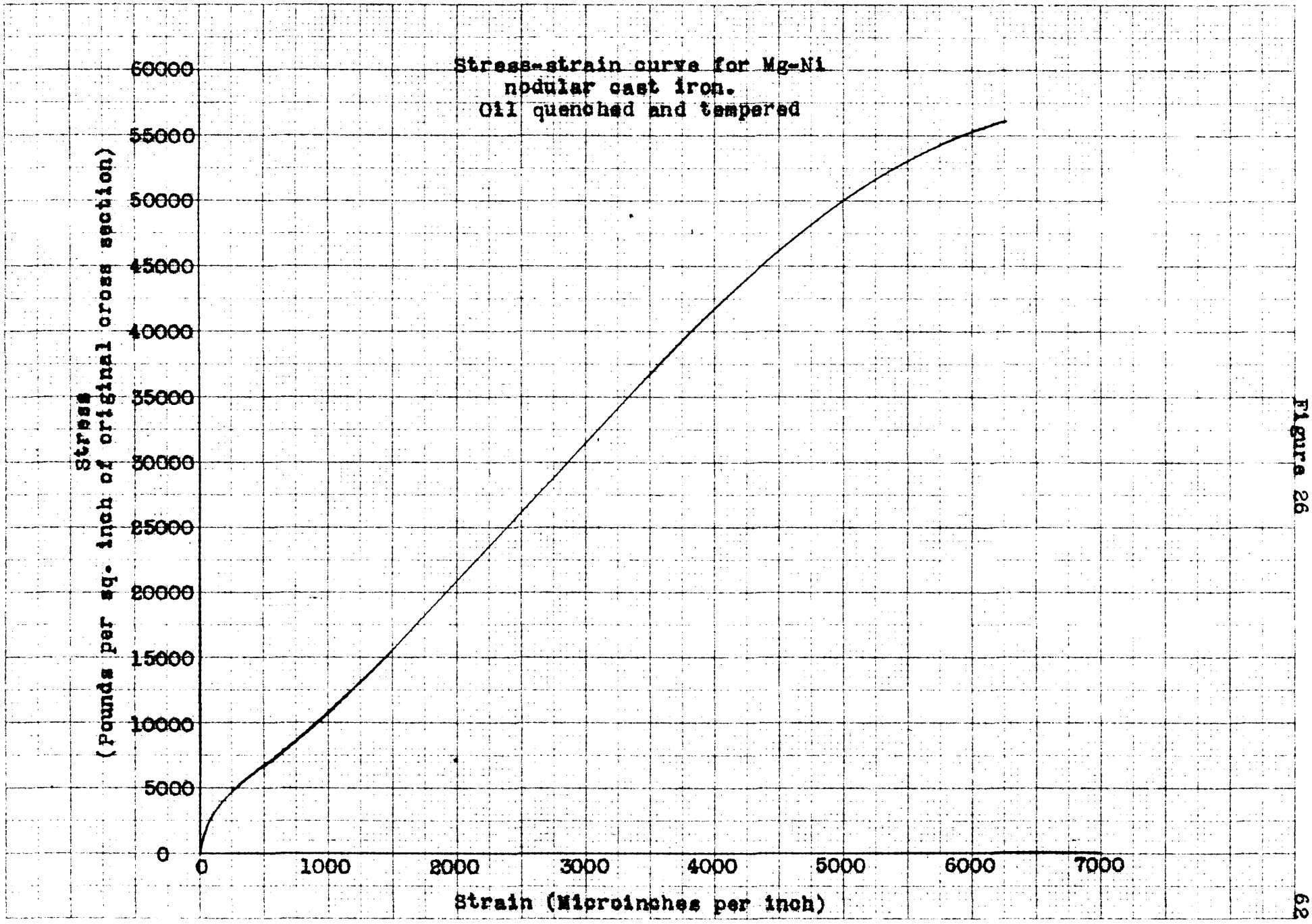

Stress-strain curve for Mg-Ni
nodular cast iron.
Oil quenched and tempered
Stress
(Pounds per sq. inch of original cross section)
60000
55000
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
0
1000
2000
3000
4000
5000
6000
7000
Strain (Microinches per inch)

Figure 26

CONCLUSIONS

The following conclusions would seem to be justified, based on the data obtained and the discussions of experimental results which are provided.

1. Nodular iron as-cast has good properties, especially when compared to most ordinary grades of gray cast iron, and a further improvement of these properties can be obtained by a suitable heat treatment.

2. Cementite decomposes in nodular iron at temperatures commonly used in the annealing of malleable iron, but it forms tiny spheroids of graphite instead of flake or temper graphite.

3. Final traces of pearlite in nodular iron microstructures are relatively persistent and are broken down only after exposure to high temperatures for long periods of time.

4. Mg-Ni nodular irons are hardenable to such a degree that their use in highly wear-resistant applications seems feasible.

5. Pearlite in the matrix of nodular cast irons may be removed by holding the iron at subcritical temperatures as in the second stage annealing of malleable cast iron.

6. With the Mg-Ni nodular iron investigated, the temperature required to produce the expected tempered microstructure in quenched specimens is higher than 1000 F when tempering periods of 3 hours or less are used.

7. Nodular iron is a versatile ferrous product and in the future should prove itself to be among the leaders in the field of engineering materials. By the proper treatment, its characteristics can be changed so that it will meet any one of a number of different requirements.

BIBLIOGRAPHY

1. Epstein, Samuel, The Alloys of Iron and Carbon, Vol. 1, 1935, pp. 396-400.

2. De Sy, Albert, Belgian Research Advances Nodular Graphite Theory, American Foundryman, January 1949, pp. 55-62.

3. Morrogh, H., Correspondence, Foundry Trade Journal, Vol. 88, March 23, 1950, p. 321.

4. Gagnebin, Albert P., Millis, Keith D., Pilling, Norman B., Ductile Cast Iron - A New Engineering Material, The Iron Age, Vol. 163, February 17, 1949, pp. 76-84.

5. Donoho, C.K., Producing Nodular Graphite With Magnesium, American Foundryman, February 1949, pp. 30-37.

6. Jeffery, W.C., Casts High Elongation Iron, American Foundryman, June 1949, p. 68.

7. Epstein, Samuel, The Alloys of Iron and Carbon, Vol. 1, 1935, pp. 40-41.

8. Rehder, J.E., An Introduction to the Annealing of Nodular Cast Iron, Transactions of the American Foundrymen's Society, Vol. 58, 1950, pp. 298-311.

9. American Foundrymen's Association, Alloy Cast Irons, Second Edition, 1944, pp. 24-26.

10. Rehder, J.E., An Introduction to the Annealing of Nodular Cast Iron, Transactions of the American Foundrymen's Society, Vol. 58, 1950, pp. 298-311.

11. Kahles, J.F., Goldhoff, R., Annealing Ductile Iron, Iron and Steel, January 1951, pp. 35-36.

12. Rehder, J.E., An Introduction to the Annealing of Nodular Cast Iron, Transactions of the American Foundryman's Society, Vol. 58, 1950, pp. 298-311.

13. Kahles, J.F., Goldhoff, R., Annealing Ductile Iron, Iron and Steel, January 1951, pp. 35-36.