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THE INFLUENCE OF SECTION SIZE
ON PROPERTIES OF
NICKEL-MOLYBDENUM CAST IRONS

Thesis for the Degree of M. S.
MICHIGAN STATE COLLEGE
Mohammed Sharif Riaz
1948

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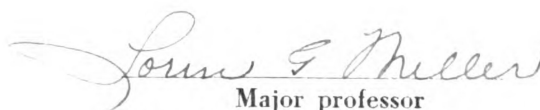
THE INFLUENCE OF SECTION SIZE
ON PROPERTIES OF
NICKEL-MOLYBDENUM CAST IRONS

presented by

Mohammed Sharif Riaz

has been accepted towards fulfillment
of the requirements for

M.S. degree in M.E.



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Date _____

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THE INFLUENCE OF SECTION SIZE ON PROPERTIES OF
NICKEL - MOLYBDENUM CAST IRONS

By

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I INTRODUCTION

A. INTRODUCTORY

1. Since the early twenties there has been a great interest among foundrymen in having better properties in cast iron. Earlier, plain irons of low carbon contents were used for castings requiring high strength. Due to poorly controlled melting practices, the foundryman found himself involved in difficulties such as poor fluidity and abnormal matrix in the irons. These irons sometimes showed good properties and at others very poor properties depending upon the kind and magnitude of the difficulty. Later some of these difficulties were overcome by the use of alloying elements. The use of nickel became common by about 1925 while Molybdenum became better known to the foundrymen by the end of the twenties.

A tensile strength of 40,000 or 45,000 pounds per square inch in 1.2 inch sections was not considered enough hence the use of alloy combinations, Ni-Cr, Mo-Cr or Ni-Cr-Mo, were adopted. The use of Molybdenum in smaller quantities was usually recommended because of its higher cost. With these alloy combinations and with better control of foundry practices it became common to melt irons of 65,000 or 70,000 psi in 1.2 inch sections.

The use of Chromium as an alloying element, alone or in combination with other alloying elements, produced irons of higher strengths but it offered one serious difficulty --- its effect of inducing chill. These irons

are usually very hard and are sometimes very difficult to machine particularly in smaller sections where it has a greater chilling tendency. Use of cast irons for crankshafts made it necessary that the irons should be easily machinable in order to meet with production requirements. Use of Molybdenum instead of Chromium became more and more general because of lesser tendency of Molybdenum to induce chill.

Work done by Kentsmith & Young¹¹, Phillips¹⁵, and Crosby⁷ in early thirties showed all round better properties of Ni-Mo irons.

In 1937, Flinn & Reese^{8*} realized that if the strength of machinable gray cast iron was to be raised above 75,000 psi in 1.2 inch sections, a structure other than pearlite was necessary. It was the time when highest strength in gray irons was associated with a matrix having 100% pearlite. Work done by various metallurgists and foundrymen in this field, among whom Flinn, Timmons & Young with their associates are notable. In England British Cast Iron Research Association has conducted an interesting research in this field. It is of interest to note that Flinn & Reese⁸ were able to cast gray iron having tensile strength equal to 105,000 psi in a 1.2" section after giving it a simple heat treatment of drawing at 700° F. The iron had a composition of 2.25% total Carbon, 2.35% Silicon, 3% Nickel and 0.81% Molybdenum. It had a structure which is now called "Acicular". This acicular structure is a characteristic of high alloy Nickel and Molybdenum irons.

* These numbers refer to the articles listed in the Bibliography.

These acicular irons are of great interest to the foundry industry.

2. The two limitations that are experienced in getting the best results from acicular irons are the presence of ferrite and pearlite in the matrix and the dispersion of massive cementite.

The complex carbides, due to their higher hardness and abrasive properties, generally make the machining of the castings very difficult. In some cases the casting may be so difficult to machine that scrapping of the casting may result.

Ferrite is the softest of the micro-constituents and its presence in the matrix lowers the properties of irons.

Contacts with the users and producers of gray alloy irons for diesel crankshafts have indicated that considerable difficulty is still being experienced in meeting with the specifications. Iron castings have either been found too hard or too soft. The difficulty would seem to be in avoiding massive carbide while keeping the acicular matrix free from ferrite and pearlite. The presence of hard cementite would be attributed to the stabilizing effect of some Chromium in the chemical composition of the iron. This would suggest an attention to Ni-Mo irons. Molybdenum is a weak chill inducer and will therefore reduce the chances of formation of hard spots which could only be avoided altogether by the addition of a balanced amount of Nickel. Besides avoiding hard spots, Ni-Mo irons could give the best known high strength acicular matrix free from both ferrite and pearlite.

3. A survey of the published literature on Ni-Mo irons has shown the difficulty of co-relating the available information.

The metallurgists and the foundrymen who have been working on acicular irons have worked with irons of different chemical composition. Some have worked with irons of as low a carbon content as 2.25%, some with as high as 3.25%, while the rest with some composition in between. It is very well known to the foundrymen using pearlite irons that the maximum use of alloying elements can be obtained with low carbon in composition. But there is a limit to the lowest desirable composition because with still lower carbon content, an iron will show poor fluidity, greater chilling tendencies and an abnormal matrix. Melting of low carbon iron also necessitates greater use of steel scrap. Further, it is rather impossible today for a cupola foundryman to melt iron of as low a composition as 2.25%. Such an iron could be melted in an electric or an air furnace. This limits the number of foundries that can use the results of a research on such extremely low carbon irons.

In addition to carbon as a variable, the silicon and manganese contents of the irons discussed in the literature also varies through wide limits. These variations in analysis of cast irons make it difficult to interpret as such much of the available data.

Although inoculation is a common practice in the melting of high strength irons, there is very little definite information concerning the relative effect of the several inoculants in common use. This introduces another variable generally not

considered in the available literature and makes it difficult to interpret the data presented on the high alloy irons.

4. The present day need of irons as high in strength as possible and existence of difficulties in co-relating the available literature gave an impetus to conduct a systematic research on acicular irons in the Laboratories of Michigan State College.

The present work is the first part of the project which will be further continued.

B: SECTION SENSITIVITY

It is now well known among foundrymen that size of a casting affects greatly the tensile strength, hardness and other properties shown by an iron. Published data on pearlitic gray irons, both plain as well as alloyed, has shown that as the section size of a casting is increased, its tensile strength goes down. The loss in the strength of a heavier section compared to some standard section, indicates the section sensitivity of the iron.

In increasing the section size the factor that affects the structure of an iron is the cooling rate. Thus the center of a thin section is cooled faster than the center of a heavier one. Cooling rate depends on many factors such as superheating temperature, temperature of iron at pouring, rate of pouring, volume of metal to be cooled, area of the surface of metal in contact with mold, conductivity of heat of the mold, amount of sand surrounding the mold position of gates and risers, and the atmospheric conditions in the foundry.

The cooling rate affects both the size and distribution of graphite flakes, and the form of matrix. Slow cooling may result in coarser graphite flakes and the inclusion of ferrite in a pearlitic matrix or as in the present case the inclusion of both ferrite and pearlite in the desired acicular matrix. A casting will have the same strength as that of a testing bar only if the cooling rates of the two are the same.

⁴
Austin in 1946 showed that "while 1.2 inches standard arbitration bar does serve to provide properties comparable with those of a casting of similar dimensions, it cannot furnish similar data for metal poured into castings having profound dimensional differences".

To illustrate this point, it will be worthwhile to consider a simple casting like a crankshaft. Crankshafts are being cast from half an inch to twelve inches journal diameter and $\frac{1}{4}$ inches to 4 inches web thickness. In the case of a crankshaft of 4" web and 12" journal diameter, evidentially journal will be much weaker if the iron used for casting is more sensitive to section size. The shaft may be even so hard that it could not be machined at a point where a change in section occurs.

It has therefore been considered that an attempt should be made to study the section sensitivity of acicular irons in order to establish basic compositions of a few irons which may later be more effectively used in the proposed extended work.

II. SURVEY OF PUBLISHED LITERATURE

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Kentsmith & Young¹¹ noted in 1932 that "the combination of Ni-Mo alloys under favorable conditions show a range of physical properties for C. I. which suggest that the matrix partakes somewhat of the properties of a high grade alloy steel". It will be worthwhile to note that they produced irons from electric furnace which had tortional strength of the order of 55,000 inch-pound.*

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Crosby⁷ in 1937 stated that acicular matrix is developed in molybdenum irons containing 1% or more of molybdenum. He further held the opinion that "certain alloy combinations enable one to secure this structure with much lower Molybdenum". In an iron of 2.9% C, 2152% Si, 1.52% Mo, he noticed martensite and retained austenite in the matrix besides acicular pearlite. He held the opinion that "acicular pearlite is most desirable for maximum impact properties."

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Roth¹⁶ in 1939 found that a low temperature draw at 600°F-700°F shows better physical properties of Ni-Mo irons.

18

In 1941, Timmons & Crosby¹⁸ found that "keeping tapping temperature above 2600°F" in the case of high strength irons when the presence of ferrite in the matrix is undesirable.

* For example, iron of composition 3.04% C, 2.24% Si, 1.2% Ni, 1.71% Mo had a tensile strength of 67,000 psi, 293 B.H.N., 5250# transverse breaking load and a tortional strength of about 55,000 inch pound. All tests were carried on 1.2" bar.

8

Interesting work has been done by Flinn & Reese⁸. They found that although acicular irons do not show much higher strength in the as cast condition as compared to the pearlitic irons, they do show markedly superior physical properties after a draw at 500-700⁰F for over 5 hours. They obtained strength consistantly above 90,000 psi in 1.2" section bars, while in one case the strength was as high as 105,000 psi. They showed that the formation of acicular structure is due to a transformation in the third region of transformation intermediate between pearlite and martensite. They attributed the formation of a second nose in the S-Curve to the presence of Molybdenum. The isothermal curves investigated by Flinn, Cohen⁹ & Chipman are noteworthy.

One of the recent contributions to the development of acicular structure has been the work carried out by the British Cast Iron Research Association. In the Fourth Report on Special Duty Cast Irons, the reporter, Mr. Pearce¹³, has presented a few points which need attention. The investigation shows that variation in Silicon content in the composition has no effect. For optimum properties carbon content should be between 2.7 to 3.1%, and Phosphorus below 0.15%. Mr. Pearce does not recommend the use of copper for heavy sections. He also recommends the use of a balanced composition of Nickel and Molybdenum and the giving of a heat treatment to the irons for better properties.

III. SCOPE OF INVESTIGATION

In the present investigation electric furnace irons were cast in 7/8, 1.2, 2, 3 and 4 inches round cylinders to determine the influence of alloy contents on section sensitivity. The base iron selected was of the following composition:

Carbon:	: 2.65-2.80%
Silicon	: 1.90-2.10%
Manganese	: 0.7-0.9%
Sulphur	: 0.05-0.08%
Phosphorus	: 0.07-0.12%

An electric furnace of indirect arc rocking type of 250 lbs capacity was used.

All the sections under consideration were tested for tensile strength and hardness and microstructures were examined in each case. In all heats test bars in 1.2" sections were tested for transverse breaking load and deflection at that load. Chemical analysis for all the heats were carried out and various results studied.

IV. MELTING PRACTICE

A. PREPARATION OF MOLDS

All the molds were made from Lake core sand. They were washed with a commercial non-carboneous wash and were dried again before use.

B. CHARGE

Three heats, each with a charge of 250 lbs, were run. The charge mainly consisted of low phosphorus, low silicon and high carbon pigs and steel scrap. Electrolytic Nickel was used for alloying and was charged while the furnace was cold. Ferro-sulphur and ferro-molybdenum were added about 10 minutes before tapping, while ferro-manganese, and silicon as ferro-silicon and calcium silicide were added about 5 minutes before tapping. A part of the total silicon content was added as an inoculant in the ladle.

The amounts of various basic charges were:

Pigs	: 170 #
Steel Scrap	: 78 #
Ferro-Sulphur (50%)	: 5 oz
Ferro-Silicon (90%)	: 11 oz
Ferro-manganese (80%)	: 5 oz
Calcium Silicide (60%)	: 1 #
Calcium Silicide (60%)*	: 15 oz

* Used as inoculant for 3 ladles, each of 70 lbs capacity.

C. INOCULATION

Research on inoculants conducted at the Engineering Experiment Station of Michigan State College during the summer 1947, showed that in the case of high strength irons a heavy inoculation of Calcium Silicide is desirable for obtaining the optimum properties from the iron. This is in agreement with the results reported by ¹³ Pearce . Pearce recommends the use of as much as 0.5% silicon of the total amount present in the iron, in the form of Calcium Silicide addition.

It was therefore designed to add about 10% of the total silicon content in the composition as Calcium Silicide into the ladle in the form of an inoculant.

In all cases, inoculant was added about 2 minutes before pouring to insure a complete solution of the inoculant in the melt.

D. TAPPING & POURING TEMPERATURES

Each melt was superheated to a temperature between 2800-2850°F before tapping. Irons were poured in all cases between 2600 to 2650°F. All the temperatures were measured by an optical pyrometer.

E. METAL CASTING

All castings were allowed to completely cool down to room temperature before they were knocked out of the flasks. Later, the castings were cleaned by wire brushing before testing.

V. INVESTIGATION

A. PROCEDURE

1. CHEMICAL COMPOSITION:

In making the chemical analysis of each sample, the drillings were obtained as follows. In the case of heat R 1, the castings were quite easy to machine in all sections while in the case of heats R 2 and R 3 irons were comparatively harder in 1.2" sections, while 4" sections were quite easy to machine. Drillings for heat R 1 were, therefore, taken from the basin of 1.2" test bar, while in the case of other heats they were taken from the hardness blocks from 4" diameter cylinders in each case. In both the last two heats drillings were taken after the hardness readings were taken. In each case each specimen was drilled half way through.

Drillings from each sample were thoroughly mixed before the analysis were carried out.

While all the irons were analysed for carbon, silicon, nickel and molybdenum, sulphur was analysed for R 1 only and manganese for heat R 2 only. Since the basic charge was the same for all the heats, the value of sulphur and manganese for the rest of the heats were considered to be approximately the same. The analysis for phosphorus, as shown in the table I is the desired composition aimed at while basic charge was calculated.

Table I shows the results of chemical analysis for each heat.

TABLE I
CHEMICAL ANALYSIS OF HEATS

HEAT .	% CHEMICAL COMPOSITION						
	C	Si	Mn	P*	S	Ni	Mo
R1 .	2.74	1.99	0.75	0.08	0.055	1.05	0.52 ^a
R2 .	2.69	1.98	0.75	0.08	0.055	0.995	1.12
R3 .	2.65	1.94	0.75	0.08	0.055	2.04	1.13

* The composition indicated is the desired analysis.

TABLE II
PHYSICAL PROPERTIES OF IRONS IN 1.2 INCH SECTION

HEAT .	Trans:	Deflec:	Tensile	B. H. N.		Mod: of
	Load, #	inches	Strength	Surface	Center	Rupture, psi.
R1 .	3740	0.3945	70,750	285	285	90,200
R2 .	4500	0.3834	76,720	321	321	119,400
R3 .	4235	0.3956	74,830	341	341	112,350

2. TRANSVERSE STRENGTH:

Four transverse test bars, of 1.2" diameter and 21" long, from each heat were broken according to A.S.T.M. specifications. Breaking load and maximum deflection at that load were recorded for each bar. The observed results were corrected by suitable correction factors in each case.

Table II shows the average results of transverse testing.

From the results obtained in transverse testing, the value of modulus of rupture was calculated according to the formula:

$$\text{Modulus of Rupture} = \text{Load in \#} \times 26.53$$

3. TENSILE STRENGTH:

Tensile test specimens were cut from the top of the lower half of cylinders in each section. In each case specimens were machined from the center portion of each bar.

Each specimen was pulled in a tensile testing machine. The results are recorded in table III. The influence of tensile strength on section size is shown in graph I.

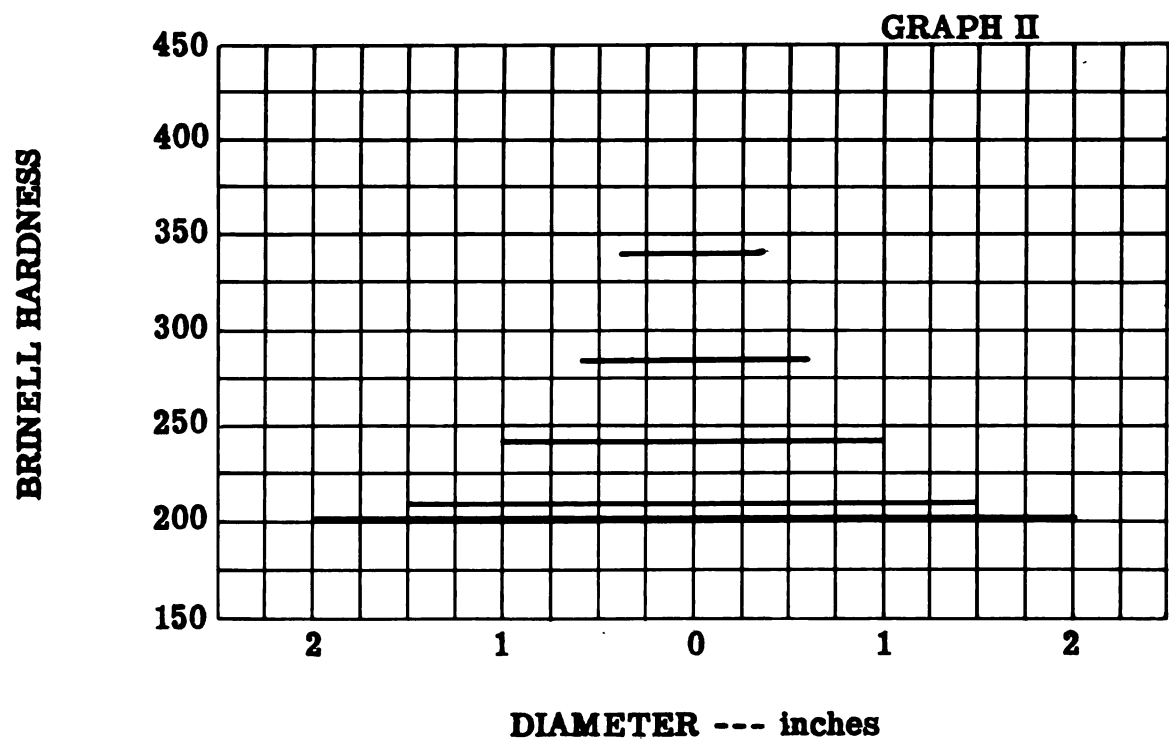
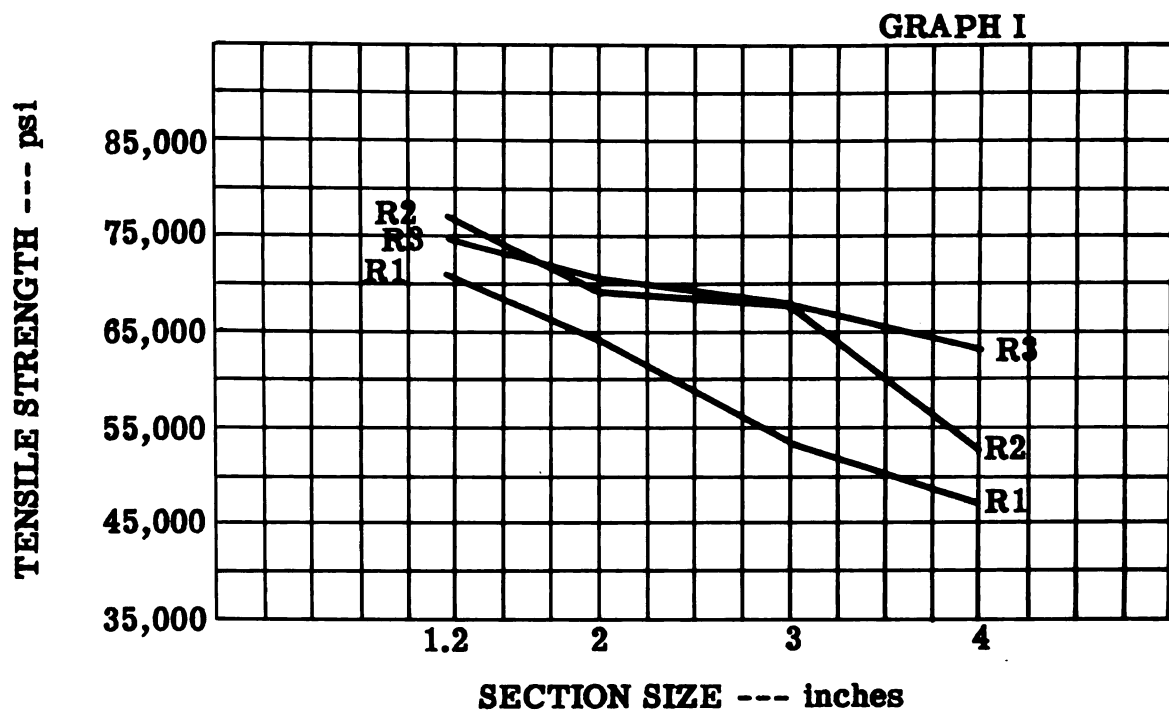
4. HARDNESS:

Hardness specimens of about one inch thickness were cut from the bottom of the top half cylinders left after cutting the tensile specimens. All specimens were well polished before any hardness reading was taken.

Hardness tests were taken at intervals of $\frac{1}{4}$ inch along

TABLE III
PHYSICAL PROPERTIES OF IRONS IN VARIOUS SECTIONS

heats	Section Tensile		Hardness		1.2 inches Test Bar		
	Size	Strength	Surface	Center	Trans: Load	Deflection	
R1	3/4	—	341	341	—	—	
	1.2	70,750	285	285	3740	0.3945	
	2.0	64,140	241	241	—	—	
	3.0	53,500	209	209	—	—	
	4.0	46,900	201	197	—	—	
R2	3/4	—	341	341	—	—	
	1.2	76,720	321	321	4500	0.3834	
	2.0	69,200	293	285	—	—	
	3.0	67,675	285	269	—	—	
	4.0	52,550	265	241	—	—	
R3	3/4	—	444	444	—	—	
	1.2	74,830	341	341	4235	0.3956	
	2.0	74,375	285	277	—	—	
	3.0	68,000	269	255	—	—	
	4.0	62,975	265	241	—	—	



HEAT R1

two diameters of each test piece. Two surface hardness readings were also taken for each case. In each case two diameters of each indentation were measured and the average of each of these two readings were recorded.

Hardness along one diameter for various sections in the various heats have been plotted in graphs II, III and IV, while surface and center hardnesses for each section have been recorded in table III. Graph V shows the effect of surface hardness on section size, while graph VI shows the influence of center hardness on the same.

5. MICROSCOPIC EXAMINATION:

Samples of about $3/8 \times 3/8 \times \frac{1}{4}$ inches were cut both at the surface and from the center. All the samples were polished in steps and final polishing was done on a silken wheel. All samples were examined both unetched and etched with 3% Nital.

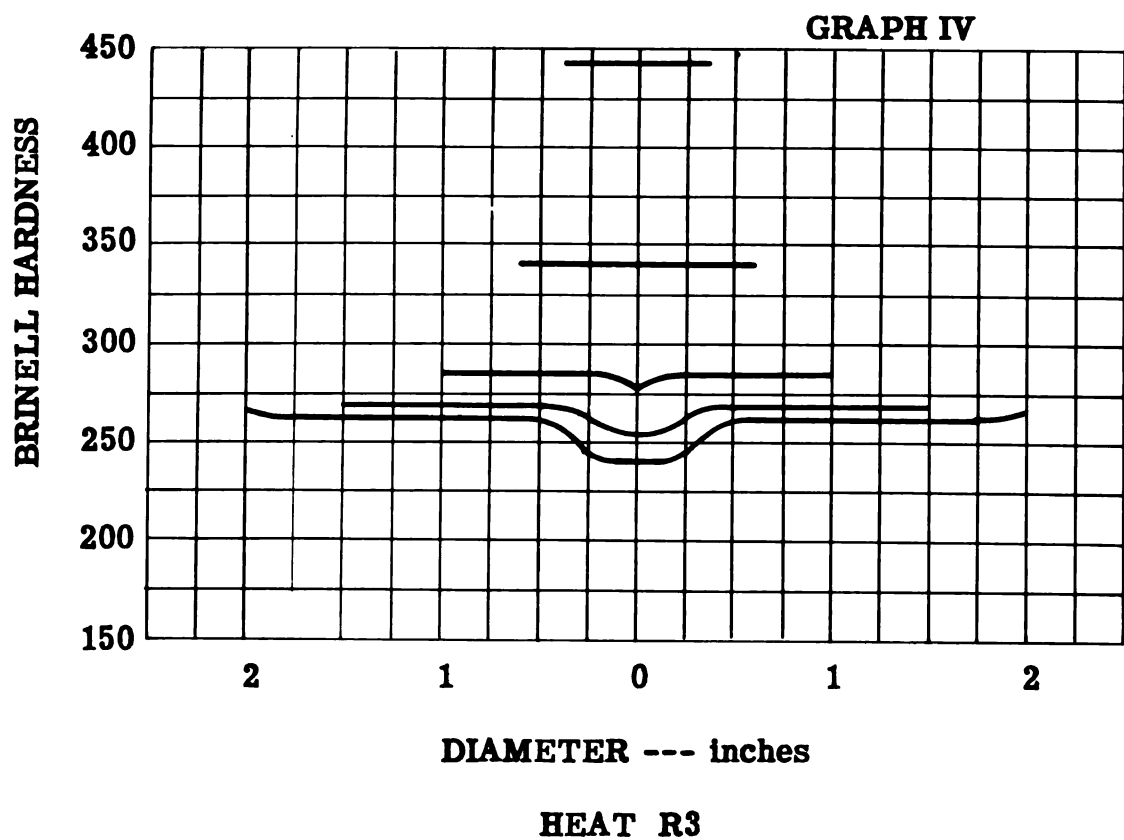
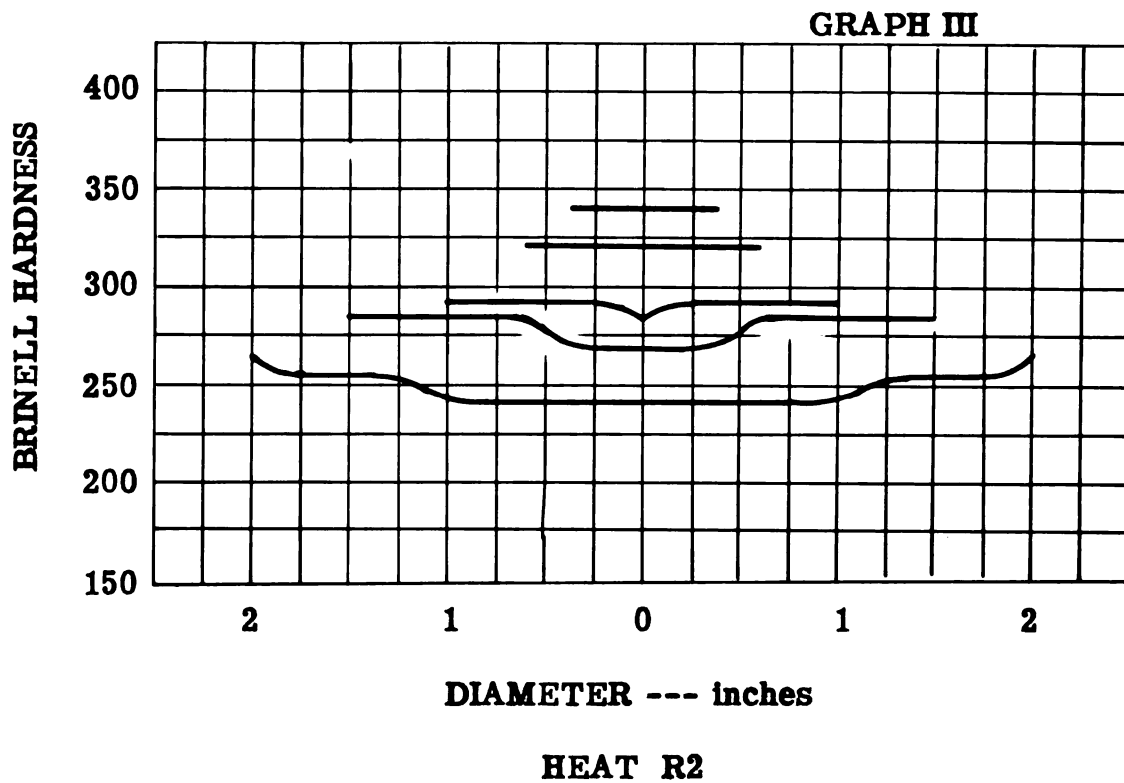
The results of micro examination have been recorded in table IV.

Photo-micrographs of 1.2" and 4" sections were taken and are shown in figures 1 to 6. All the photo-micrographs were taken near the surface of the specimens concerned.

B. DISCUSSION

1 TENSILE STRENGTH:

Tensile strength in the case of heat R1 decreases quite rapidly up to 4" section. The presence of ferrite and the change in matrix seems to be the main cause of rapid decrease of tensile strength as compared to other heats.



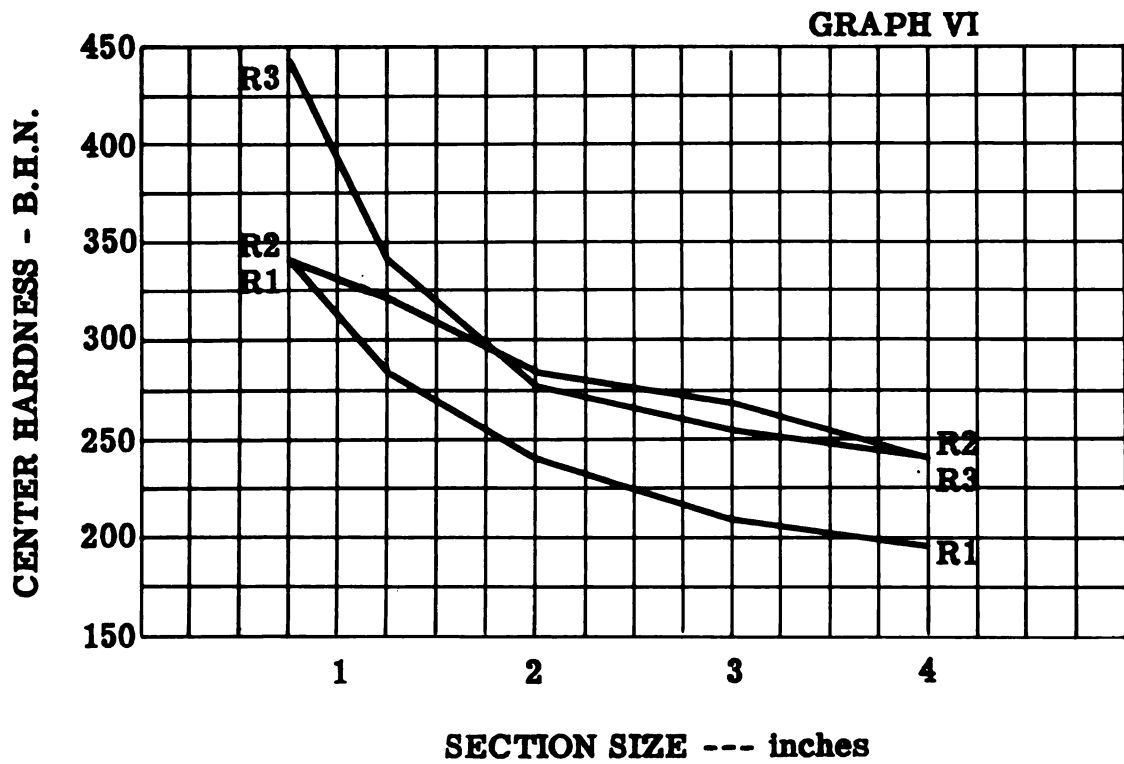
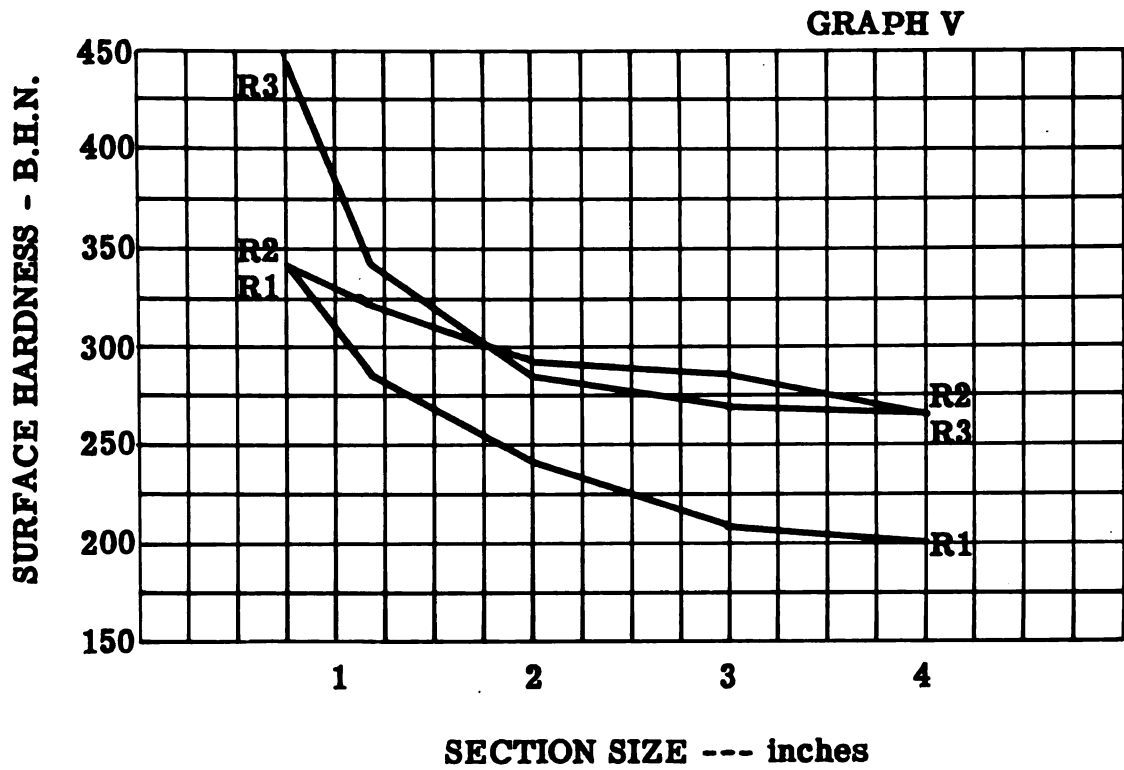
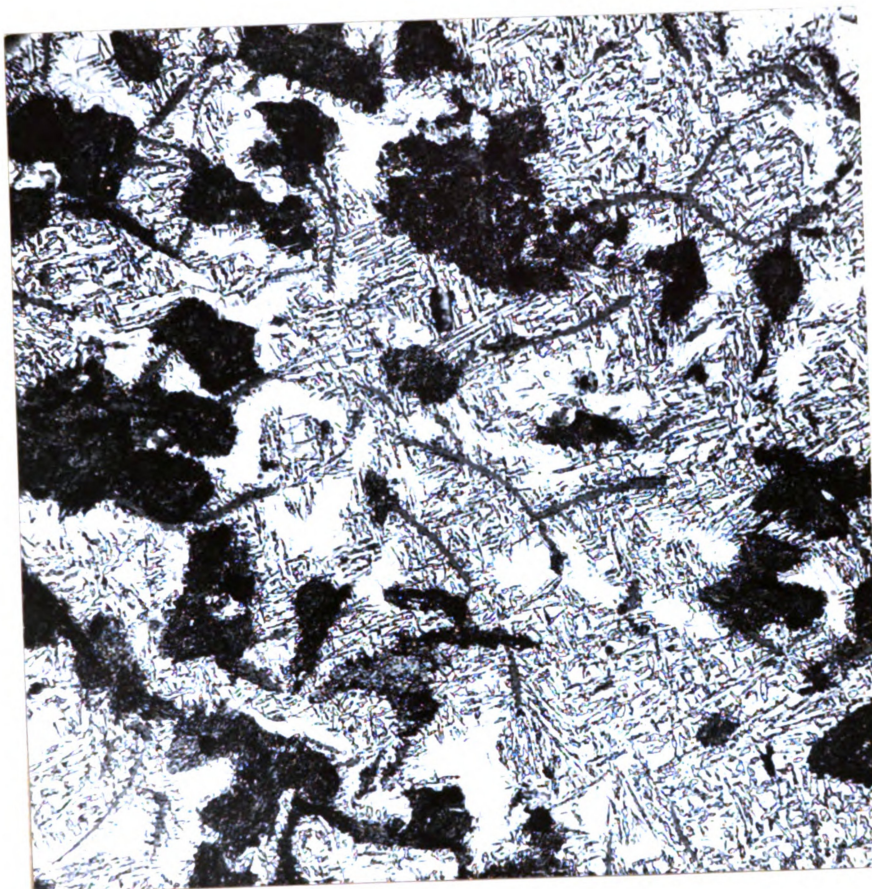


TABLE IV
SUMMARY OF MICROSCOPIC EXAMINATION RESULTS

SECT SIZE	HEAT R1	HEAT R2	HEAT R3
3/4	Structure similar to fig 5 with somewhat finer flakes	Structure similar to fig 5.	Structure similar to fig 5 with a greater proportion of martensite.
1.2	Dendrites of very fine pearlite, areas of acicular structure, some martensite, & fine graphite. See fig 1.	Structure entirely acicular, some martensite & fine dispersion of massive carbides. See fig 3.	Acicular structure with areas of martensite. Fig 5.
2.0	Structure similar to with much less ferrite.	Structure similar to fig 3 with some fine pearlite.	Structure similar to fig 5.
3.0	Structure similar to fig 2 with less ferrite.	Structure similar to A large amount of fine pearlite, some acicular structure, with a small amount of martensite & massive carbides. Graphite flakes somewhat coarser than 2 inch section size,	Structure similar to fig 5 with some fine dispersion of massive cementite.
4.0	Large amount of pearlite & ferrite with coarser flakes. See fig 2.	Matrix largely fine pearlitic with some ferrite along flakes & some inclusions of massive carbides. See fig 4.	Acicular matrix with some martensite. Shows massive carbide & coarser flakes. See fig 6.

N.B.: 1. Matrix in all cases was found to be uniform from surface to center.

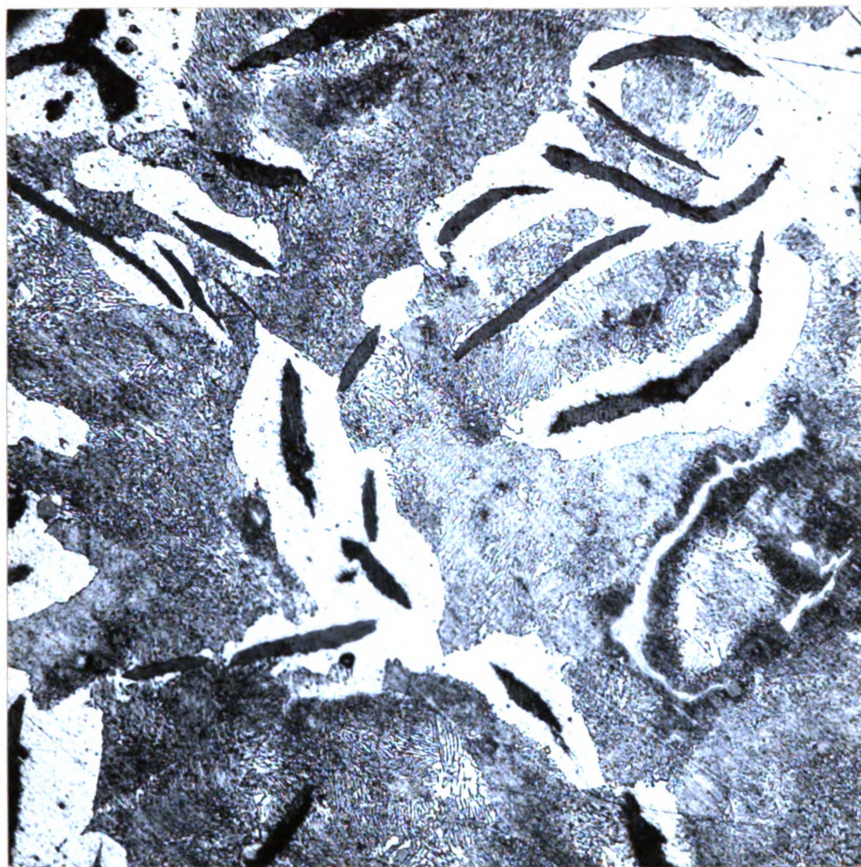
2. Graphite distribution in all cases was found normal.



IRON R1, SECTION 1.2 INCHES

ETCHED WITH 3% NITAL, 250X

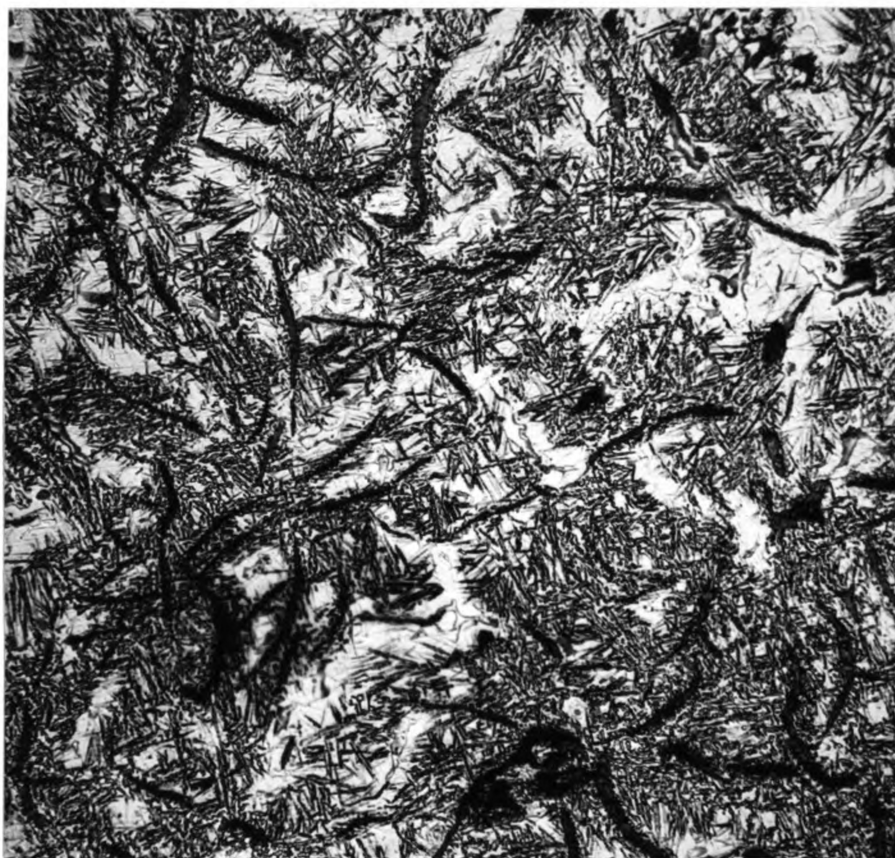
Fig 1



IRON R1, SECTION 4 INCHES

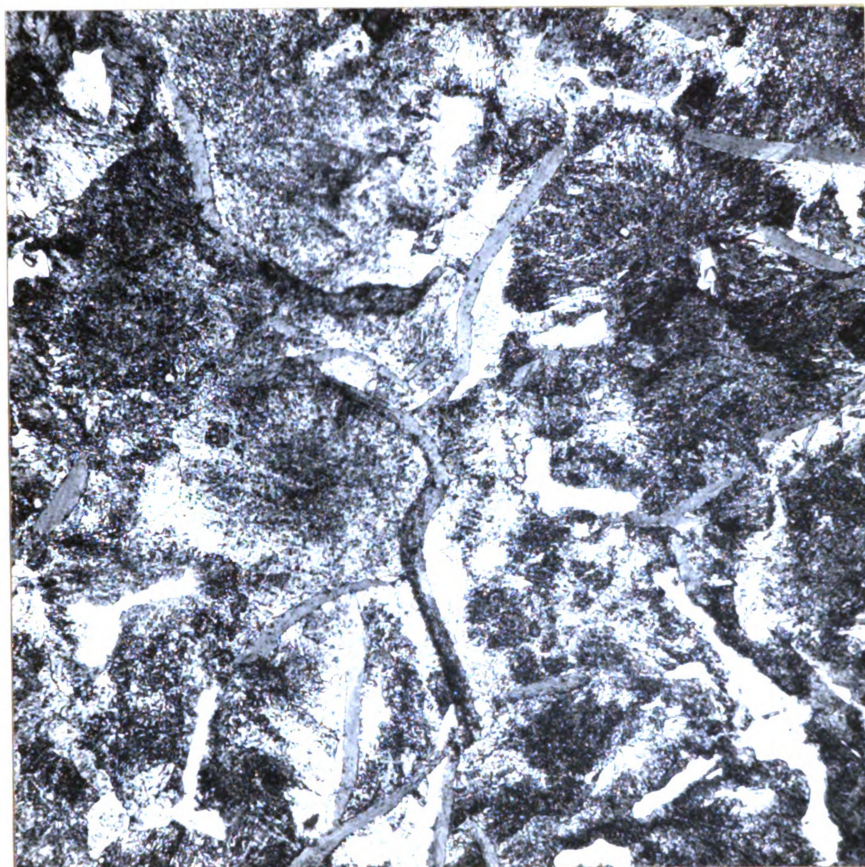
ETCHED WITH 3% NITAL, 250X

Fig 2



IRON R2, SECTION 1.2 INCHES
ETCHED WITH 3% NITAL, 250X.

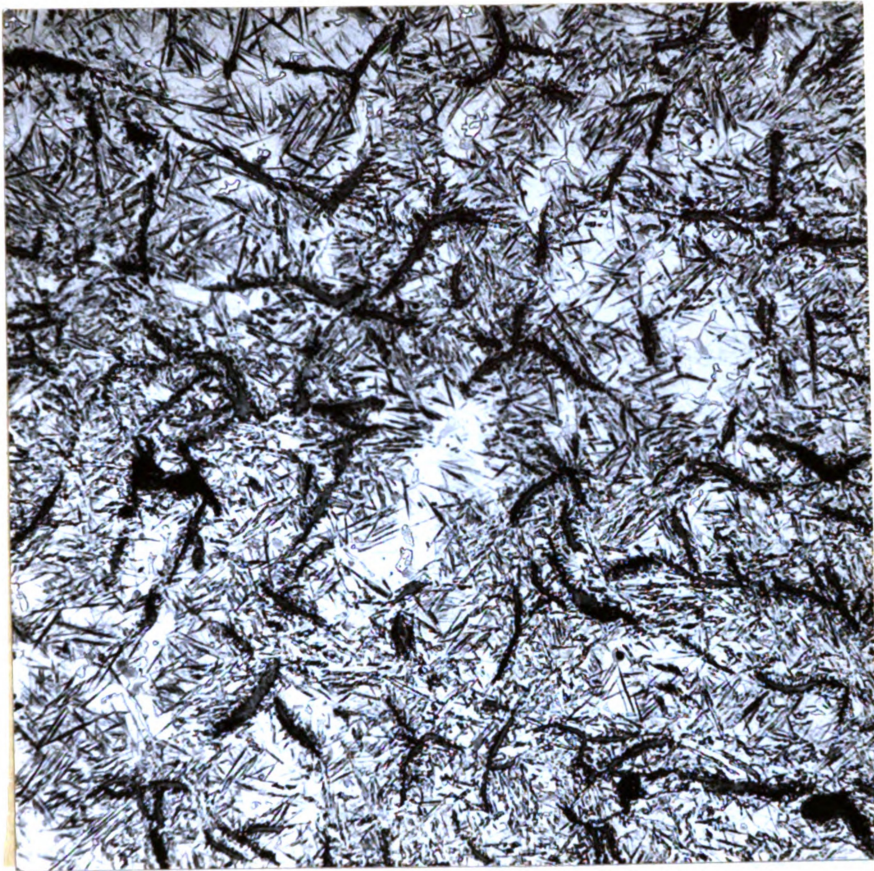
Fig 3.



IRON R2, SECTION 4 INCHES

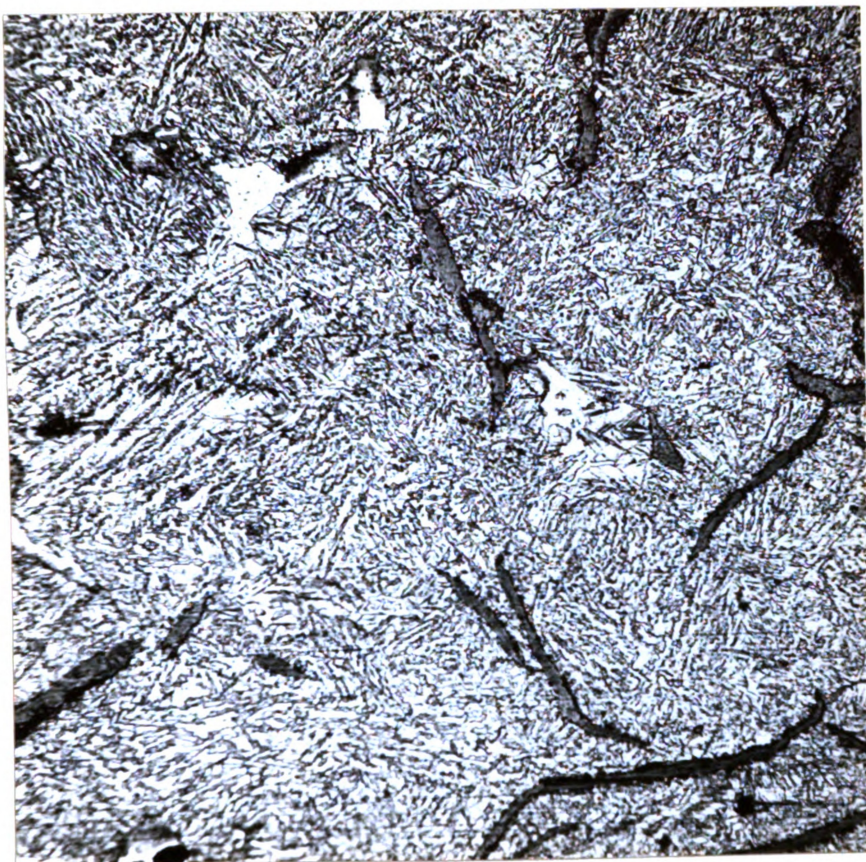
ETCHED WITH 3% NITAL, 250X.

Fig 4



IRON R3, SECTION 1.2 INCHES
ETCHED WITH 3% NITAL, 250X.

Fig 5.



IRON R3, SECTION 4 INCHES

ETCHED WITH 3% NITAL, 250X

Fig 6

It is very interesting to note that the tensile strength in sections up to 3" do not differ much in heats R2 and R3, while in heat R3, matrix does not change by far up to the section sizes considered, in heat R2, the matrix of 4" section is largely pearlitic as compared to 3" section which has only areas of fine pearlite. The presence of pearlite and some ferrite near graphite flakes in 4" section in heat R2 decreased the tensile strength rapidly.

2. HARDNESS:

In the case of heat R1, hardness throughout all the sections was fairly uniform. However, in the heaviest section, a drop of 4 Brinell only was recorded for the center hardness as compared to the rest of the section which was quite uniform throughout.

An increase of molybdenum to 1% produces an iron somewhat less uniform in hardness from center to surface. (Compare graphs I & II).

A further increase of nickel by 1% in iron R2, seems to have made the iron closer and denser in heavier sections and has resulted in a somewhat greater uniformity of hardness along diameters in each section.

It will be interesting to note that hardness in sections up to 2" is uniform throughout the section.

Surface hardness and center hardness graphs reveal interesting results. In both the graphs curves for heats R1 and R3 follow more or less similar slopes.

It may be noted here that heat R3 had double the amount of alloying elements than heat R1.

In the case of heats R2 and R3, there does not seem to be much difference between surface hardnesses and the center hardnesses for sections 1.5 to 4 inches.

3. MICRO-STRUCTURE:

Micro examination of all heats revealed a normal distribution of graphite all through the matrix in all sections.

The structure of matrix was found fairly uniform throughout the section in all sections except in 3 & 4 inch sections in heats R2 & R3, in which case a coarser matrix was noted near the center as compared to the structure near the surface. It is due to this coarser structure that the hardness near the centers of these sections is less than at other points of the section.

While no pearlite appears in various sections of heat R3, it is found to appear first in 1.2" in heat R1 and in 2" section in heat R2. It may further be noted that in heat R1, ferrite appears in all sections above 1.2" and that some ferrite shows up along graphite flakes in 4" section in heat R2. There was no massive ferrite found in R3 in any section under consideration.

The effect of variation in matrix of different sections in each heat on the various properties of each iron has been discussed under those properties.

4. TOUGHNESS:

It will be seen that deflection in 1.2 inch section in all these irons varies more or less in the same way as does the transverse breaking load. This shows that the toughness of all the irons considered also varies directly with the variations in the breaking load.

Accordingly iron R2 shows greater toughness than iron R3.

5. MACHINABILITY:

There is no standard test for machinability. It was, therefore, decided that a comparison of machinability of irons in various sections may be made from the ease with which each tensile test specimen is machined. It was found that except for 1.2" section in iron R3, it was not difficult to cut tensile specimens from the rest. The difficulty in machining 1.2" section of heat R3 could be attributed to the presence of martensite in the matrix.

VI. SUMMARY

An investigation has been carried out to determine the composition of a Ni-Mo iron suitable for castings of section up to 4 inches. A composition can be regarded suitable for a given section when it has an acicular matrix free from massive ferrite and pearlite or large amounts of massive carbides.

This investigation reveals that an iron of the following approximate composition C 2.75%, Si 2%, Mn 0.75%, Ni 2% and Mo 1% is suitable for the range of sections 1.2 inch to 4 inches round.

The iron is acicular in this range of sections and contains a small amount of very finely dispersed massive cementite. This iron is readily machinable in all sections down to 1.2" round. Due to the presence of martensite in the section, 1.2" section can be machined although with some difficulty. It is believed that the machinability and the physical properties of this iron can be further improved by drawing at some suitable temperature.

The iron produced a tensile strength ranging from 74,000 psi in 1.2" sections to 62,000 psi in 4" section, with a range of surface Brinell hardness from 341 to 265 in the respective sections.

Iron R1 of composition C 2.75%, Si 2%, Mn 0.75%, Ni 1% , and Mo 0.5% showed a pearlitic structure in 1.2" section while iron R2 of composition C 2.7%, Si 2%, Mn 0.75%, Ni 1% and Mo 1% is entirely acicular up to 2" round sections and shows areas of fine pearlite in 2 inch and heavier sections.

It is planned to continue this investigation to determine the effect of drawing and of drawing and quenching on the properties of iron R3.

VII. BIBLIOGRAPHY

Although there is not much published literature concerning Nickel-Molybdenum Alloy Cast Iron, yet an attempt has been made to list herein related material which was considered useful in carrying on the research. A list of the Publications indexed has also been added.

In the bibliography, besides the usual abbreviations for the months of the year, the following common abbreviations - v, n, p, H.T. and C. I. for volume, number, page, Heat Treatment and Cast Irons, respectively - have also been used.

A. PUBLICATIONS INDEXED: The following is the list of the publications indexed in the bibliography.

- AFA - American Foundrymen's Association
Transactions (Chicago)
American Foundrymen - (Chicago)
- ASM - American Society for Metals
(Cleveland, USA) Transactions
- ASTM - American Society of Testing
Materials, Proceedings
- Auto Engr.-Automobile Engineer, Monthly Journal
of the Institution of Automobile
Engineers (London)
- Foundry - The Foundry, Monthly, (Cleveland, USA).
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21. Young, E. R. and others.
1938 Physical Properties of C. I. in Heavy
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AFA, n46, p891.

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