THE UNIVERSITY OF MICHIGAN

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MODERN HIGH CARBON FERROUS METALS FOR RESISTANCE TO SURFACE DAMAGE

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INTRODUCTION

Metallurgical developments during the last decade have provided impressive additions to the metals in the high carbon ferrous field available for use in specialized and general applications where resistance to surface damage, as well as inherent mechanical strength is important. The group includes a broad range of supporting mechanical properties which allow use of the materials for severely stressed applications in which wear or corrosion are factors in service life. Cast metals are particularly suited to use in these applications because parts can be designed for minimum machining, with desired intricacies, and for production at lower cost than most other methods of fabrication. In addition, metals which would be impossible, or at best extremely costly, to machine can be produced by casting as the only economical method of manufacture.

Each application for metals imposes particular conditions which make generalization from laboratory or limited service data on wear or corrosion performance inadequate for most purposes in specification of the same metals under different operating conditions. Therefore, the engineer is faced with the need to examine available materials and make his selection on the basis of experience and known operating conditions of the application.

High carbon ferrous materials afford microstructures which satisfy the classical idea, particularly with respect to wear, that metals should possess duplexed structures with hard and soft phases to improve lubrication and provide strength properties. These materials consist of either graphite in a harder metallic matrix, or of iron carbide in a similar matrix which is softer than the iron carbide. Graphite structures vary considerably among the graphitic materials in the family and, in fact, one interesting and important application utilizes a metal with a controlled mixture of graphite and iron carbide. Castings for application in which corrosion is a factor are produced from alloyed irons which provide corrosion or stain resistant matrices.

The technical literature is liberally sprinkled with data reporting service performance of various high carbon cast materials or the results of laboratory tests on the same materials. Unfortunately, not much agreement, except in general form, can be reached when slightly different wear or corrosive conditions are imposed. This often results in misapplication of some metals, or the use of one metal which, while adequate, does not deliver performance equal to another which might be available. In fact, recent developments have provided metals with properties superior for certain applications in such rapid sequence that service experience has not been able to keep pace. Therefore, the present paper will be concerned primarily with a review of modern metals in the high carbon ferrous family, their structures and properties, and post-production processes which can be utilized to develop uniquely desirable characteristics for specific applications.

High carbon ferrous metals may be divided into several groups which describe the basic microstructures of the metals and intimate the type application for which they are suitable. These are:

1. Graphitic, with matrix consisting of transformation products from austenite. These metals have good static and impact strength. They are generally used under lubricated wear conditions.
2. Graphitic, with corrosion resistant austenite matrix. This type structure is produced by alloying. Static and impact properties are good. The metals are generally used where damage by corrosion, or a combination of corrosion and moderate wear, is encountered.
3. Carbidic, with matrix consisting of transformation products from austenite. These metals lack static and impact strength, but possess high resistance to abrasive wear.
4. Duplexed structure, with both graphite and primary carbide in a matrix of transformation products of austenite. These possess intermediate static and impact properties. They are used under conditions of boundary lubrication, severe lubricated wear, or abrasion.

Graphitic Materials

It has been said that high carbon graphitic materials provide the ideal microstructures for resistance to wear conditions, because of the presence of graphite which provides self-lubrication and pockets on the surface to contain lubricant, as well as small abrasive particles which might reach wear surfaces. Alloying and heat treatment provide matrix structures ranging from low carbon spheroidized cementite in ferrite, through martensite, to austenite which permit wide range in service performance and in supporting mechanical properties. The graphite bearing materials may be divided into three types on the basis of the shape and distribution of the graphite particles. These are:

1. Gray cast iron---flake graphite.
2. Malleable and pearlitic malleable iron---temper carbon graphite.
3. Nodular iron---nodular or spherulitic graphite.

Gray cast iron is characterized by the presence of free carbon or graphite in the form of flakes which, in three dimensions, are roughly in the shape of potato chips. A photomicrograph shows the cross-section of the flake, resulting in an irregular linear graphite structure. The matrix structures may range from ferrite, which is very soft, through pearlite, bainite and martensite to austenite, depending on composition. Hardness ranges from about 100 BHN to 512 BHN.

Malleable and pearlitic malleable iron contain graphite produced by annealing a white iron structure. The graphite occurs in an irregular rounded shape, producing a three-dimensional figure similar to popped corn. The matrix can consist of ferrite, in the case of malleable iron, or various combinations of iron carbide in ferrite, which produces a series of pearlitic malleable irons. The hardest structure consists of a martensitic matrix produced by oil quenching and has a hardness of 555 - 652 BHN.

Nodular irons are characterized by graphite in an essentially spherical form. The rounded graphite can be produced by magnesium treatment of low sulfur molten iron, in which case the graphite is generally formed during solidification of the casting. Rounded graphite of the same type is also produced commercially by casting an iron with elevated sulfur content, which solidifies white and is then annealed to produce the spheroidal graphite structure. Matrix structures of these irons range from ferrite through martensite, with a range of hardness approximately the same as that developed in malleable and pearlitic malleable iron.

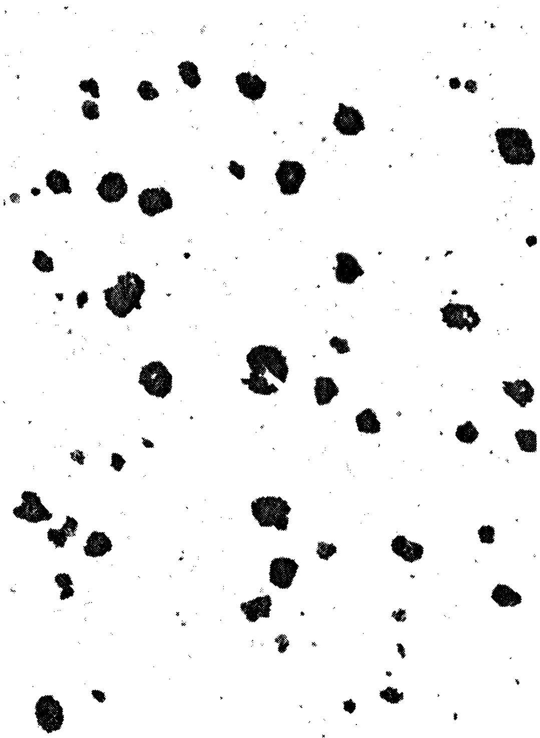
Figure 1 illustrates the graphite structures encountered in high carbon ferrous materials and demonstrates the difference in the graphite shape and distribution. The flake shape obviously provides maximum interference to the continuity of the metallic matrix and results in the lowest mechanical properties for a particular matrix. The rounded shapes of the temper carbon and nodular graphite provide less discontinuity in the matrix and permit higher levels of mechanical properties. Generally, the flake graphite structure produces lowest elastic modulus and most efficient damping of vibration. Metals with the rounded graphite shapes have higher elastic modulus, higher strength, and less efficient damping. All of the graphite bearing metals possess damping characteristics superior to those of steel, which makes this family of metals particularly desirable for applications where noise or vibration is undesirable and resistance to surface damage must be considered.

Gray Cast Iron

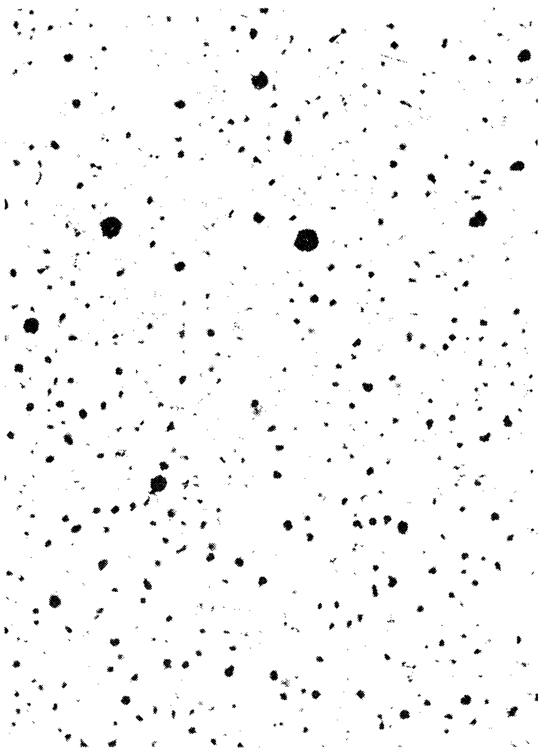
Gray cast iron is generally melted in a cupola and cast in green sand molds. The flake graphite forms during solidification of the iron and is not changed in shape or distribution by subsequent heat

Flake
Gray Iron

Temper Carbon
Malleable & Pearlitic Malleable Iron



Rounded Duplexed
Spherulitic & Random Structure
Nodular Irons



Spherulitic
Nodular Irons

Figure 1. Typical Graphite Structures in Modern High Carbon Ferrous Alloys.

treatment. High strength irons may be desired for special applications and may be duplexed, such as by cupola melting and electric furnace refining, or may be melted in an electric furnace. In any case, the flake graphite form is developed during solidification.

Since most cast iron is not heat treated, the matrix structure in the final part is that developed during cooling in the mold after solidification. Some control can be exerted through the use of alloying elements, or through the balance of the basic carbon and silicon contents of the molten iron. Additional control is applied through control of shakeout temperature, when slow cooling in the green sand mold is discontinued and more rapid air cooling, which provides a harder, fine matrix structure, takes place.

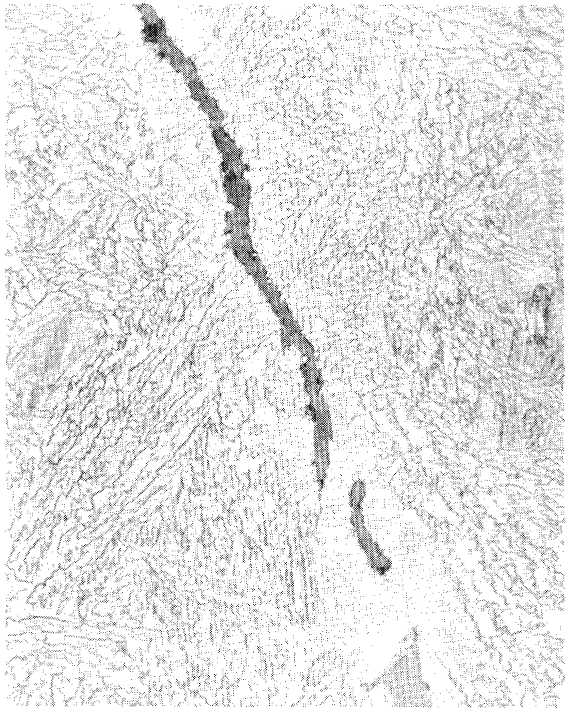
Because the basic structure of gray iron castings is developed during solidification and cooling, these castings exhibit section sensitivity. Thin sections tend to be harder and have finer microstructures than heavier sections. In fact, castings with very thin and very thick metal sections might have white iron corners or thin sections and excessively soft heavy sections. Good control of composition, melting practice, and cooling rate will minimize differences in structure and properties within a casting and produce a high quality product.

Figure 2 shows three typical matrix microstructures which can be developed in gray cast iron through control of alloy composition. The first photomicrograph shows a typical lamellar pearlite matrix with a minimum of free ferrite. The pearlite has a tensile strength of approximately 120,000 psi and a hardness of about 241 BHN. Because gray iron normally contains approximately 3.25% carbon---of which approximately 2.5% by weight is in the form of flake graphite---the overall strength of the casting and its hardness are below that of the matrix structure. Graphitic carbon occupies approximately three times the volume of the same weight of pearlite. Therefore, the graphite content of gray cast iron is about 7.50% by volume. This results in tensile strengths of 30,000 - 50,000 psi in unalloyed pearlitic type gray cast irons.

On the other hand, the presence of a relatively large volume of flake graphite in a random distribution provides an excellent wear surface with properties for self-lubrication and with voids to contain fluid lubricant or to trap abrasive particles which might enter the bearing surface. This material possesses a high damping capacity, which is often a desirable factor in the use of gray iron in parts subject to vibration and possible noise in service.

The addition of alloy elements, such as nickel, chromium, molybdenum, vanadium, copper, and manganese, permits development of harder, stronger matrix microstructures in gray iron castings. The change in structure resulting from addition of nickel and molybdenum is shown in the second photomicrograph in Figure 2. The matrix consists of bainite produced during continuous cooling of the casting through temperatures ranging between 900° and 600°F. Bainite is stronger, harder, and tougher than pearlite, and is capable of

No Alloy
Pearlite & Ferrite in Matrix



Ni-Mo Alloy
Bainite Matrix

Ni-Cu-Cr Alloy
Austenite Matrix

Figure 2. Microstructures of Typical Gray Cast Irons. (500X - Etched)

considerable work hardening. This may be an important factor in bearing applications where the development of a superficial work hardened skin would contribute improved service life.

The third photomicrograph in Figure 2 illustrates a gray cast iron with an austenitic matrix developed by alloying with nickel, copper, and chromium. This structure is typical of a material known as Ni-resist which contains nominally 14% nickel, 6% copper and 2% chromium. It is tough and ductile and has excellent resistance to corrosion. Similar austentic matrix microstructures occur in more highly alloyed metals, such as a 30% nickel, 6% chromium stain resisting iron.

Gray cast irons respond to hardening heat treatments and can be satisfactorily flame or induction hardened to produce thin wear surfaces for special applications. Occasional difficulty does occur in these operations, because of the inherent characteristics of gray iron. In some cases, attempts to quench harden result in cracking, due to the low ductility imparted by the random thin flake graphite structure. In others, a satisfactory hard surface is produced in that portion of the metal heated to temperatures above approximately 1400°F before quenching. At a greater depth beneath the surface, where temperatures did not reach 1400°F but exceeded approximately 1250°F, the metal undergoes partial or complete graphitization, and thus is considerably softened. In some applications this condition may be undesirable.

Malleable & Pearlitic Malleable

Malleable and pearlitic malleable iron are produced by heat treating white iron castings. The graphite is in the form of nodules and is developed during an annealing heat treatment at 1700 - 1750°F. Since the casting as produced in the foundry has all the carbon in the combined form, heat treatment produces a uniform structure throughout the final part. There is little chance of excessive variations in the final structure, because of the process used in manufacture. The primary difficulty in the production of these materials is the limitation on the maximum section thickness which can be produced. Most malleable foundries limit their production to a maximum of about 1-1/2" thickness, to permit melting of a balanced composition which will produce a white iron structure as cast, and will completely anneal in practical time periods.

Malleable iron, which consists of a ferrite matrix with uniformly distributed nodules of free carbon, is not generally suitable for wear applications. The ferrite is soft and ductile and can be readily damaged in metal-to-metal contact or by the presence of minor abrasive contamination. Malleable iron does have a natural resistance to corrosion under moderately severe conditions, and is used for many applications where other ferrous materials are unsuitable because of a lesser corrosion resistance.

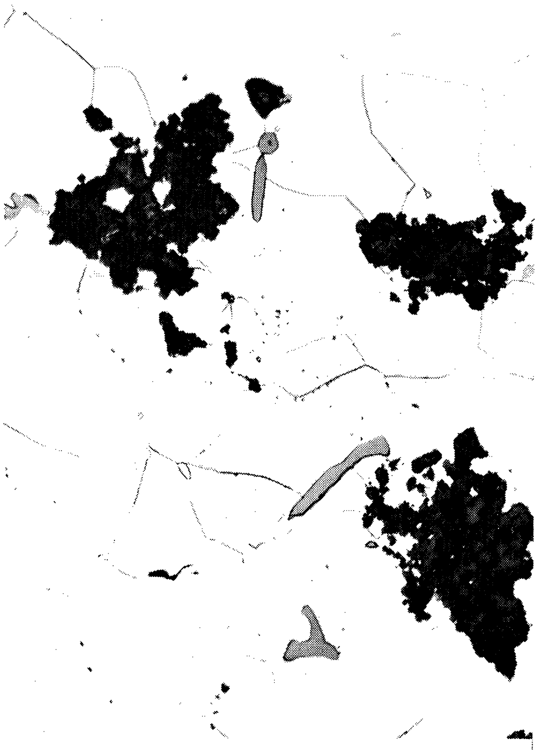
Pearlitic malleable iron, because of the heat treatment utilized in its production, is a versatile material with structures ranging from a low concentration of spheroidized carbides in the matrix, to a fully martensitic matrix. Yield strengths range from 45,000 to 90,000 psi and hardnesses from 170 - 321 BHN.

Figure 3 illustrates the range in microstructures available in malleable and pearlitic malleable iron. The upper left hand photograph is ferritic malleable iron with essentially no combined carbon. The upper right hand photograph is a pearlitic malleable which has been tempered to a low hardness. During tempering the combined carbon content was reduced to .27%, and the carbide particles were spheroidized to produce the low resulting hardness. The two lower photographs illustrate higher carbon matrix structures; one spheroidized, but not graphitized in tempering heat treatment, and the other merely tempered to produce the required hardness from the oil quenched martensite matrix. Because of the range in combined carbon and matrix microstructures which can be produced in pearlitic malleable, wide ranges in mechanical properties can be produced to accommodate applied service loads.

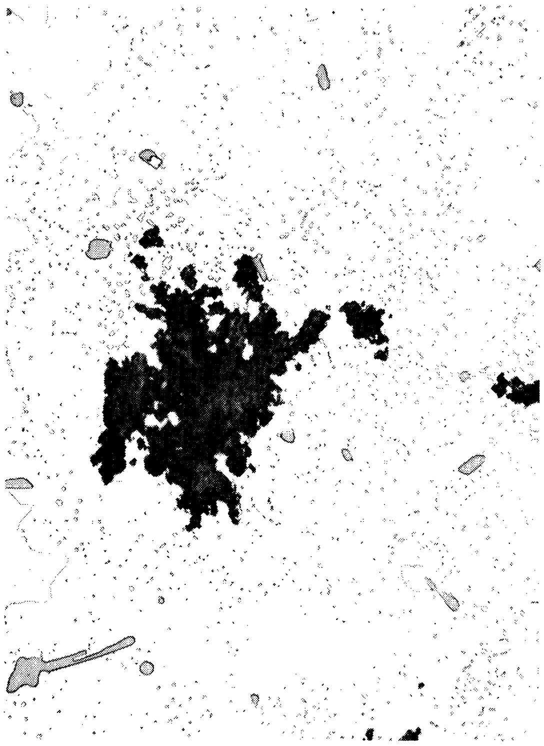
Pearlitic malleable iron is not generally alloyed, because alloys which would stabilize cementite, particularly chromium, vanadium and tungsten would make annealing heat treatment excessively long or impossible, unless the alloys were balanced with a suitable amount of a graphitizing element. Further, some alloying elements have different effects on graphitization during solidification and during annealing heat treatment, making proper balance and control difficult or impossible. Alloying elements to improve hardenability which do not effect graphitization can be produced in pearlitic, are not generally required to produce hardenability during heat treatment. Certain special applications may require alloying elements for development of specific requirements.

Pearlitic malleable lends itself to post-production heat treatments, because of the excellent natural hardenability of the material and the presence of randomly distributed graphite throughout its structure. The graphite acts as a source of carbon in the event that higher combined carbon contents are required, or as a depository for carbon that must be removed from the matrix structure. A hardenability band for a typical pearlitic malleable iron is shown in Figure 4. It will be noted that the data are presented in two forms; one as measured by Rockwell C hardness testing, which is presented in the broken lines, and the other as measured by micro hardness tests with a Tukon tester, and presented in the solid curves. The hardness of the quenched end of the Jominy bar ranges from 58 - 63 Rockwell C, and the depth of hardening is approximately equivalent to that of a 8640 or 4140 steel.

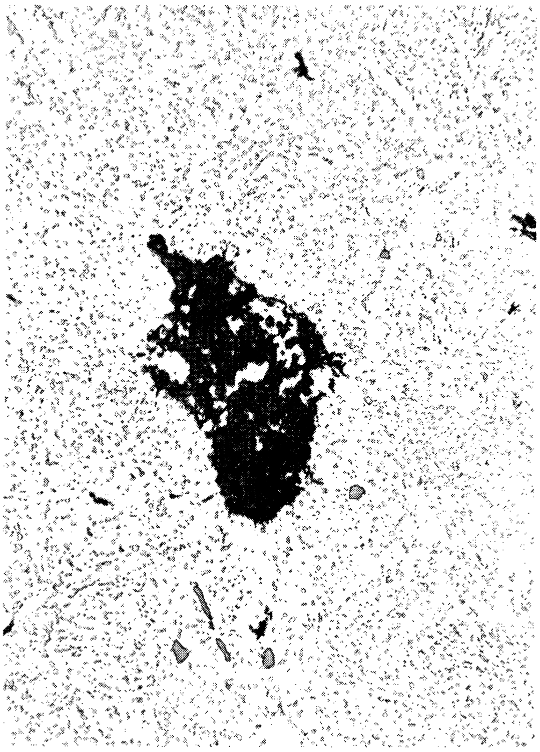
It is of particular importance that recognition be taken of the actual micro hardness of the matrix, since this is one of the controlling factors in service performance of a part. The presence of



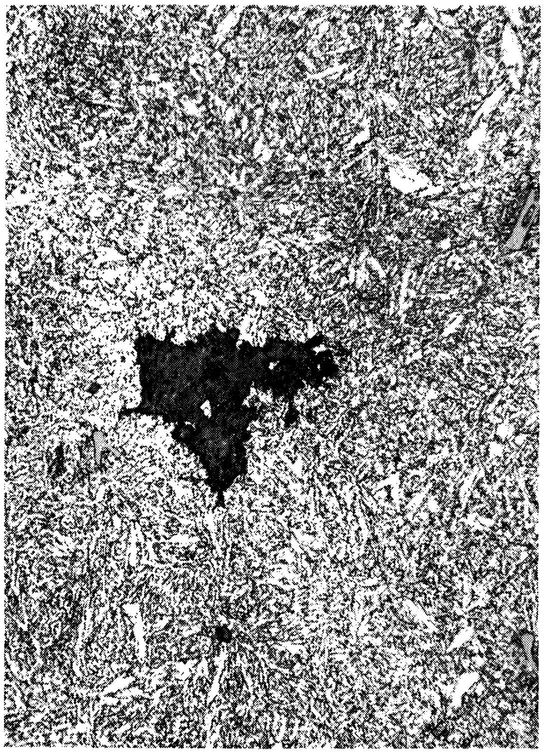
0.03% Combined Carbon
137 BHN



0.27% Combined Carbon
Spheroidite - 170 BHN



0.63% Combined Carbon
Spheroidite - 207 BHN



0.67% Combined Carbon
Tempered Martensite - 255 BHN

Figure 3. Pearlitic Malleable Irons with Controlled Combined Carbon Content & Matrix Structure. (500X - Etched)

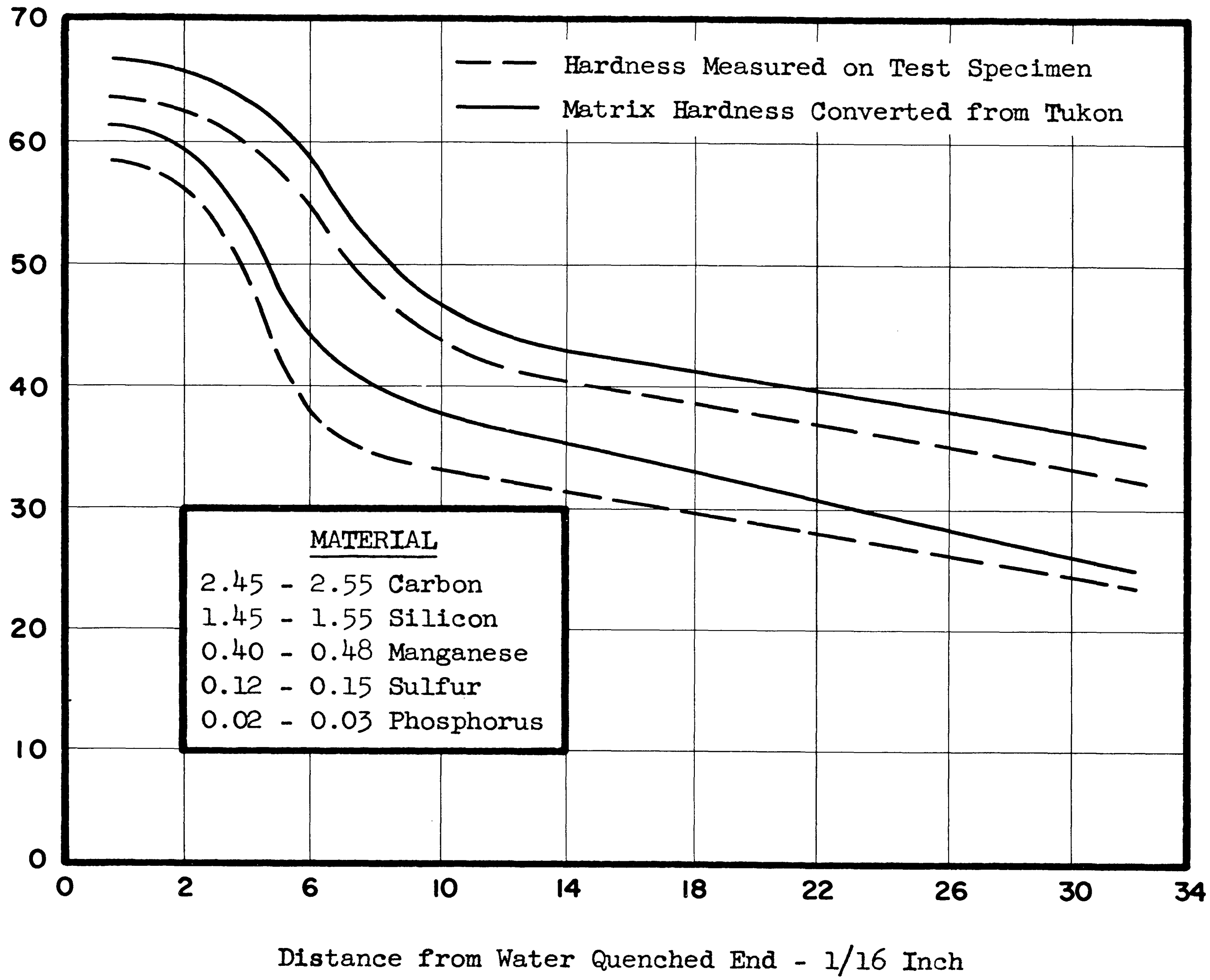


Figure 4. Hardenability Band for Pearlitic Malleable Iron.

about 1.75% carbon as free graphite (5% by volume) reduces the averaged hardness as measured by a Rockwell tester to a value considerably lower than actual matrix hardness. The wear characteristics of the heat treated metal are controlled by the matrix or micro hardness, not the averaged Rockwell C hardness.

Depth hardness curves for induction heated and flame heated pearlitic malleable are shown in Figure 5. Maximum averaged hardnesses of 56 - 58 Rockwell C (61 - 63 Rockwell converted from Tukon) were produced on the surface, and the penetration of the hardened zone was over .100". Variations in rate of heat input permit control of depth of hardening to lesser or greater amounts, depending on service requirements. Both oil quenched and drawn and air quenched and drawn material can be satisfactorily hardened, provided adequate combined carbon exists in the base pearlitic iron castings. Experience has shown that pearlitic malleable with combined carbon content of .4% or greater will produce maximum surface hardness, while lower carbon pearlitic malleable produces lower surface hardness. Generally, castings with minimum 177 BHN will contain at least .4% combined carbon and will be satisfactory for surface hardening treatments.

Pearlitic malleable iron in intermediate or high hardness ranges (197 - 321 BHN) is often satisfactory for applications involving moderately severe wear conditions. Where the conditions require additional resistance, surface hardening can be applied. This then provides a structural part with high levels of strength, rigidity, and toughness produced at low cost and with wear surfaces fortified by post-production heat treatment.

Malleable Base Spheroidal Iron

Malleable base spheroidal iron is similar to both pearlitic malleable and to the well-known ductile iron produced by magnesium treatment of low sulfur, high carbon base iron. It is produced by fortifying malleable base iron with sulfer to a content in the range of about .3 - .6%, casting white, and heat treating to produce a graphitic structure. The heat treatment utilized for this material is the same as that used for pearlitic malleable. However, the resulting product differs from pearlitic malleable, in that the graphite nodules are spheroidal rather than the roughened rounded type typical of pearlitic malleable. The spheroidal nodules may consist of a spherulitic graphite center surrounded by amorphous free carbon, or may be completely spherulitic.

Malleable base spheroidal iron is unique in the high carbon ferrous castings field in that carbon in excess of the amount soluble in austenite at high temperature can be decomposed readily to graphite, while that carbon dissolved in austenite at high temperature produces an extremely stable carbide which is difficult, if not impossible to decompose at sub-critical temperatures.

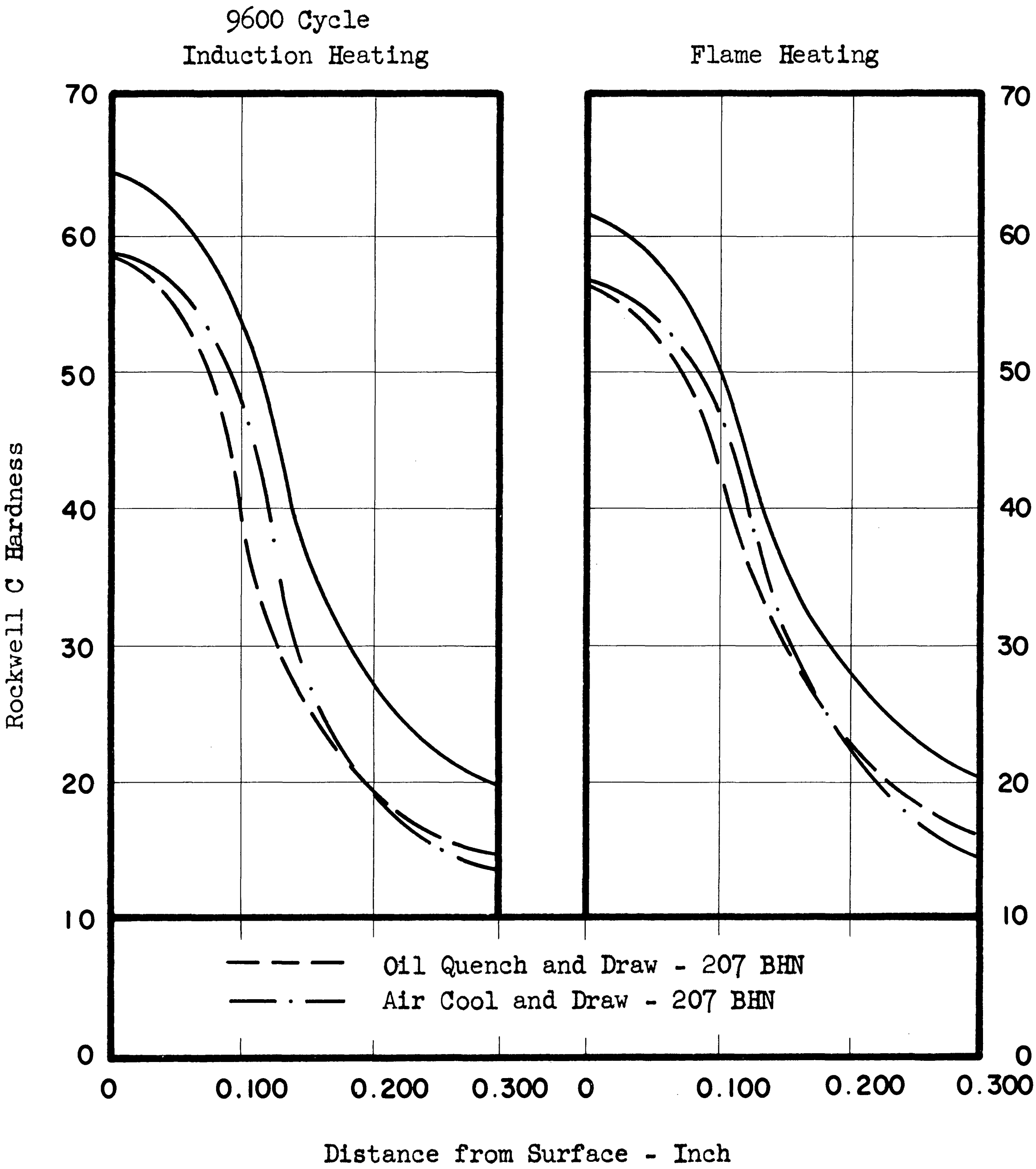


Figure 5. Depth - Hardness Relationships for Surface Hardened Pearlitic Malleable Irons.

Figure 6 illustrates the marked stability of matrix carbides, as evidenced by the uniformity in hardness and microstructure of castings drawn for long time periods at temperatures ranging from 1100 - 1345°F. During these draw heat treatments, the initial martensitic matrix produced by oil quenching was spheroidized, but did not undergo second stage graphitization, even in areas adjacent to existing graphite particles. Because of this characteristic of the material, very uniform matrix structures can be developed during heat treatment, and relationship of tensile properties to hardness is somewhat better than that for pearlitic malleable irons. This is illustrated in Figure 7. Tensile properties-hardness relationship illustrates the superiority of reheated, oil quenched, and tempered pearlitic malleable or malleable base spheroidal iron (Spher-A-Steel) over air quenched and tempered material at the same hardness. It also shows the higher ratio of tensile and yield strength to hardness for the more uniform sulfur bearing, malleable base spheroidal iron.

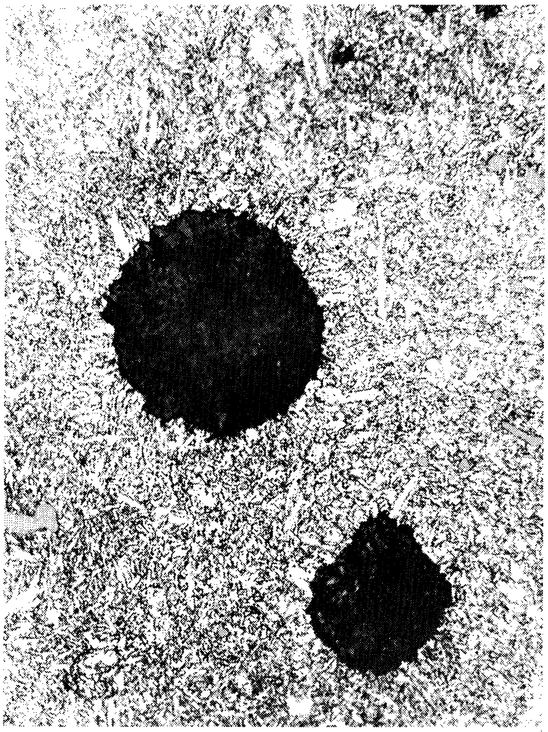
Figure 8 illustrates an important characteristic of malleable base spheroidal iron which permits its use for special applications requiring extreme surface hardness and a strong uniform back-up material. The specimen illustrated in the photomicrographs was an oil quenched and tempered casting which was dry cyanided two hours at 1340 - 1350°F. and air cooled. The atmosphere consisted of 40% RX gas, 20% natural gas, and 40% ammonia. A case depth of .0065" resulted. This treatment would be impractical in any of the other graphite bearing, high carbon materials because of their tendency to graphitize on heating in the range of 1300 - 1350°F. This is the temperature range in which second stage graphitization of malleable, gray, or nodular iron occurs to produce a ferritic matrix.

Malleable base spheroidal iron extends the section thickness which can be cast in a malleable type material, in that the presence of sulfur retards graphitization during solidification and permits production of white iron castings in sections at least 10" thick. These can then be annealed to produce the desired graphite-bearing microstructure.

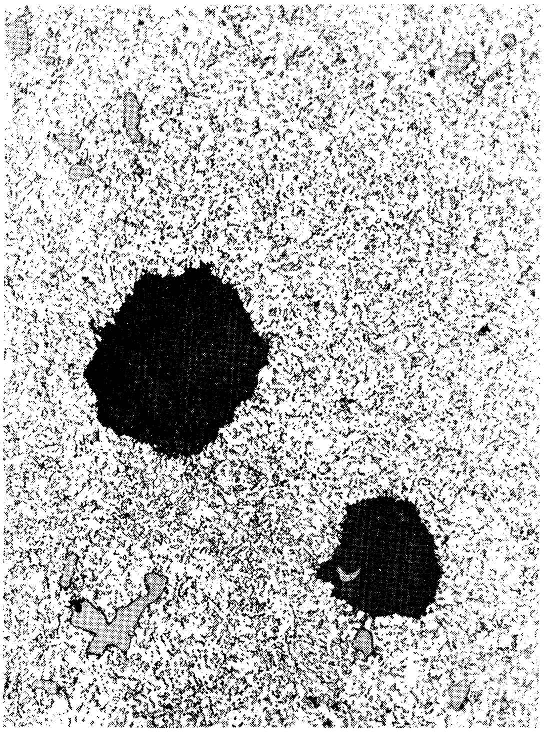
Service experience has indicated that malleable base spheroidal iron has a higher co-efficient of friction than either gray iron or pearlitic malleable, which makes it a potentially valuable material for clutch discs and other applications where the effects of sliding friction are desired. This, coupled with the uniformity of the matrix structure and its superior basic wear resistance, results in a material with wide application.

Nodular (Ductile) Iron

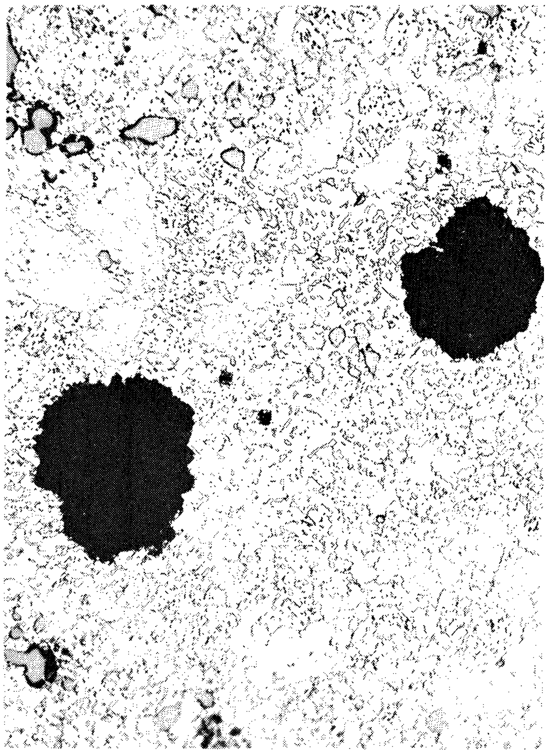
Nodular iron is produced by adding magnesium or combinations of magnesium and cerium to a low sulfur base iron in order that graphite formed during solidification will be spherulitic rather than flake. The base iron is generally of high carbon content (3.0 - 3.6% carbon), and the molten metal is inoculated with silicon prior to casting to promote



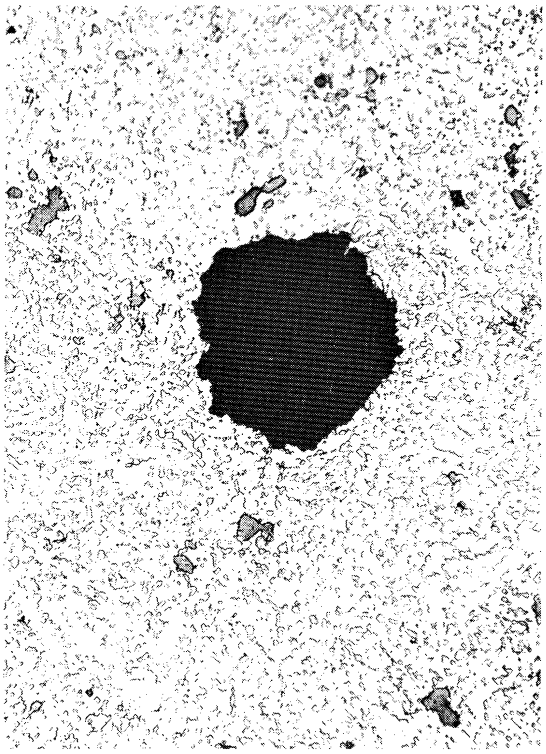
1100°F. 16 Hours
269 BHN



1200°F. 19 Hours
217 BHN



1300°F. 16 Hours
207 BHN



1345°F. 16 Hours
212 BHN

Figure 6. Microstructures of Oil Quenched Malleable Base Spheroidal Iron Drawn for Long Time Periods at Various Temperatures. (500X - Etched)

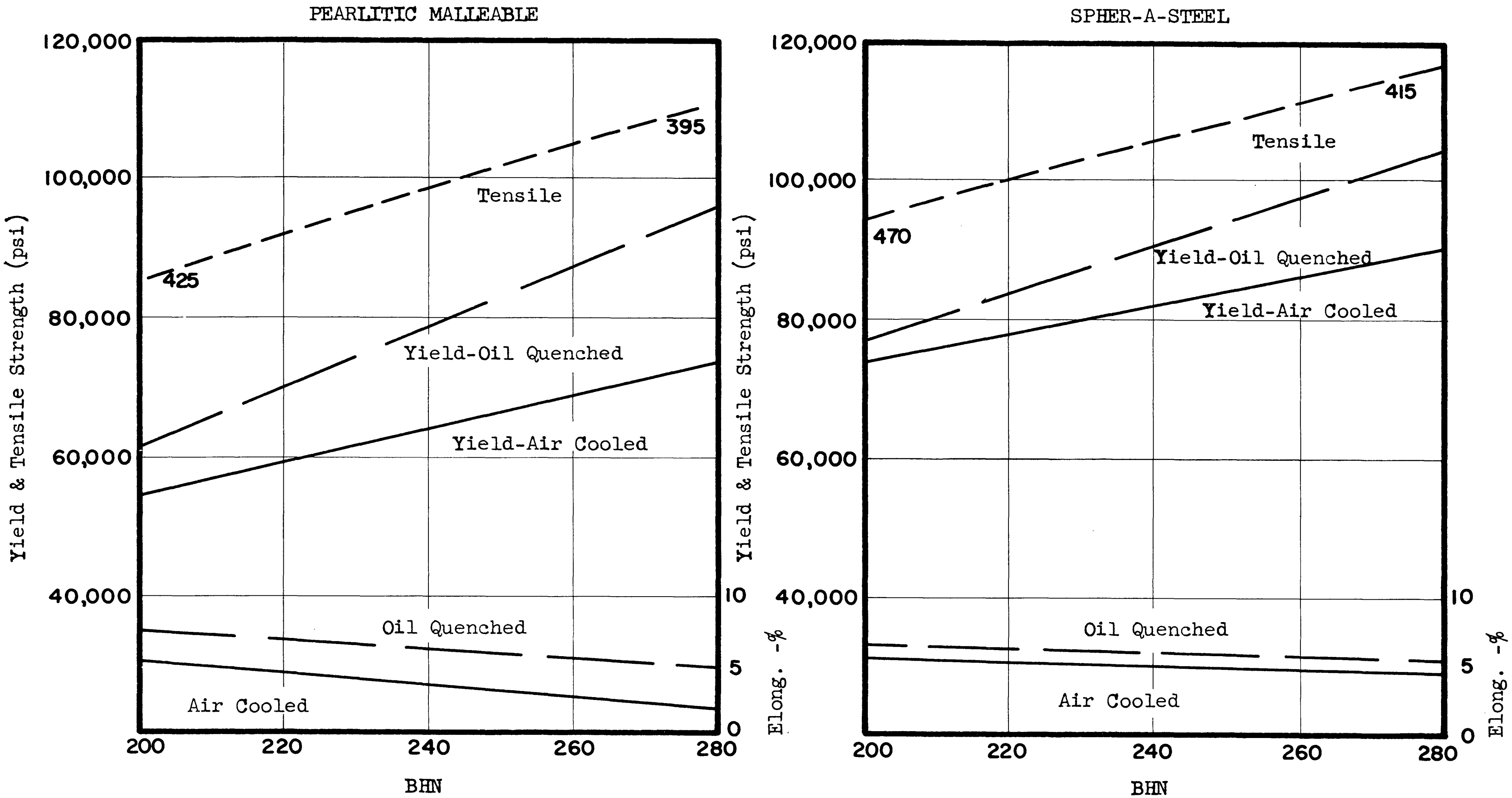
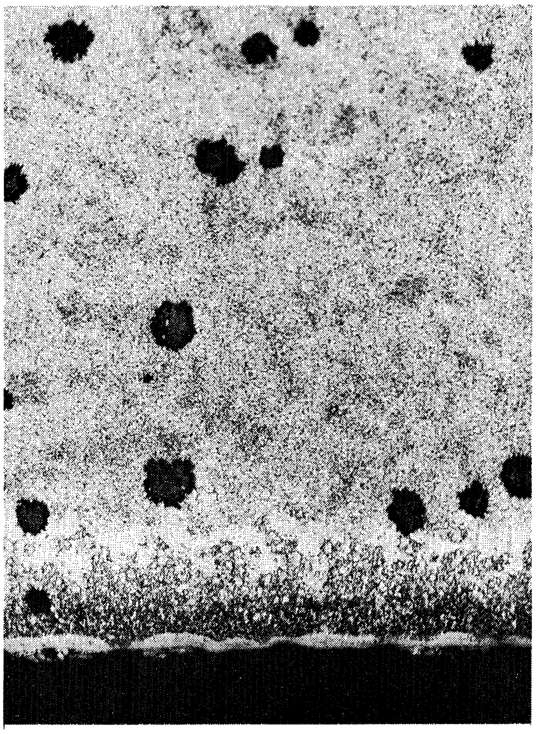


Figure 7 Tensile Properties - Hardness Relationships for Pearlitic Malleable Iron and Spher-A-Steel



100X Etched

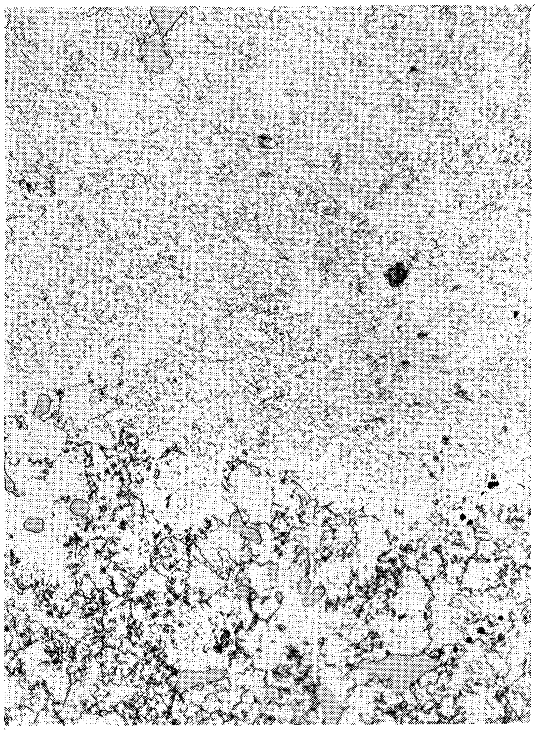


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Figure 8. Surface Microstructure of Dry Cyanided Spher-A-Steel.

graphite formation. Castings with metal sections 1/2" or thicker can be produced free of primary carbide as cast, while thinner sections usually contain some primary carbide and require annealing to develop a strong, machinable structure.

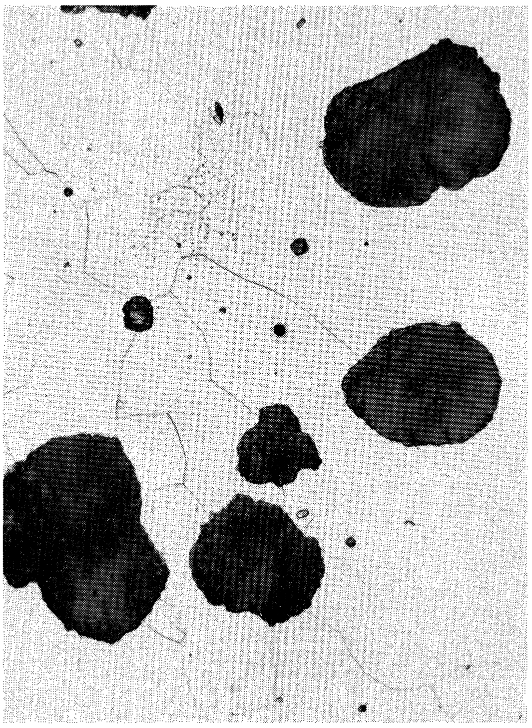
Mechanical properties of nodular iron are similar to those of malleable and pearlitic malleable iron having the same matrix structure and hardness. It will respond to hardening heat treatments and to surface hardening treatments in the same way as pearlitic malleable.

Because nodular iron is not restricted to a requirement that structure be free of graphite as cast, it is possible to balance the composition and to alloy to produce heat and stain resisting matrix structures for resistance to corrosive conditions. Figure 9 illustrates the similarity of matrix structure of nodular iron and pearlitic malleable and demonstrates, in the lower right photograph, the formation of an austenitic corrosion resistant matrix produced by the use of alloys. This material is similar to Ni-resist discussed under the heading of gray cast iron, except that the graphite shape is spherulitic, and the properties of the material are superior to those obtainable in Ni-resist because of the graphite shape. Austenitic nodular iron has many applications for resistance to corrosion which can not be satisfactorily serviced by other existing high carbon ferrous castings.

Controlled Chill Hardenable Cast Iron

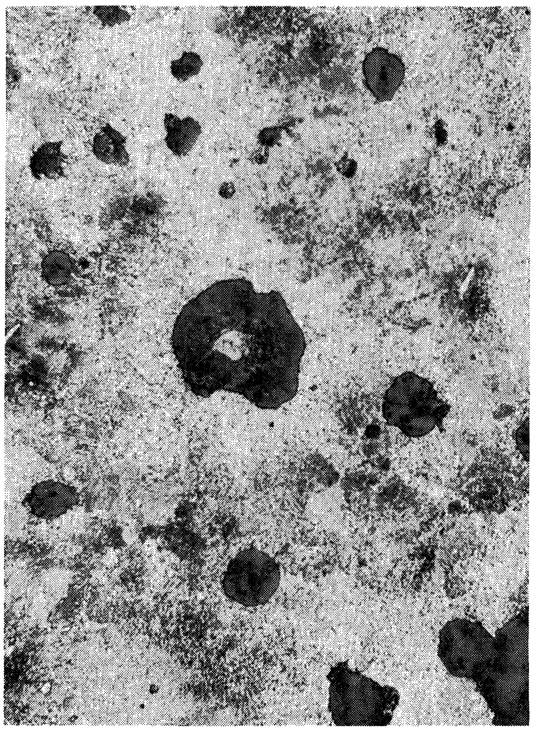
A unique application of a material having a balanced composition to produce a heterogenous structure is demonstrated by controlled chill hardenable cast iron. This material is produced to close compositional limits and is alloyed in an electric furnace to produce castings containing, simultaneous, flake graphite, primary carbide and a bainitic or pearlitic matrix with high hardenability. A typical microstructure is illustrated in Figure 10.

The metal is melted and conditioned to a precise chill characteristic which will develop the desired microstructure in the casting to be produced. For service, castings are ground to size, then hardened to 57 - 64 Rockwell C. The part then has abrasion resistance contributed by cementite, the desirable characteristic of graphite, and a hard matrix. While a mixed cementite and graphite structure is generally considered undesirable, controlled chill hardenable iron produced under controlled conditions has valuable properties for special applications. One reason for its wear and abrasion resistance is the presence of alloying elements which prevent the formation of ferrite in the graphitic areas and which lend hardenability during heat treatment.

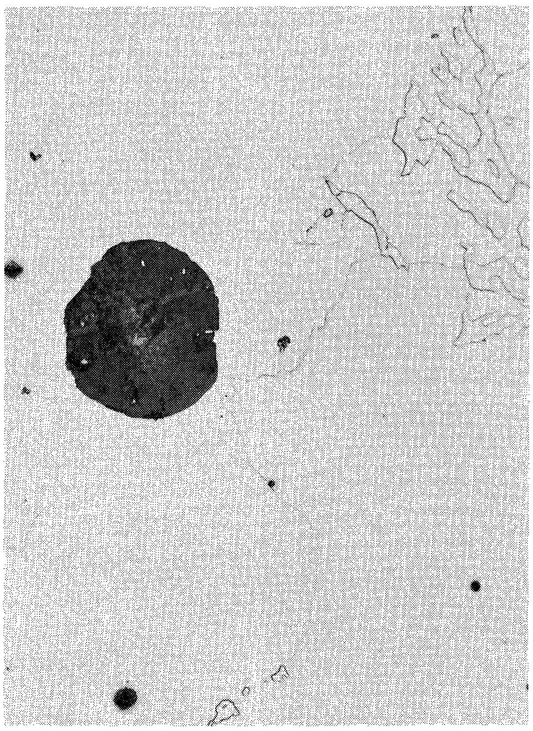


No Alloy - Annealed
Ferrite Matrix - 149 BHN

No Alloy - As-Cast
Pearlite & Ferrite Matrix - 217 BHN

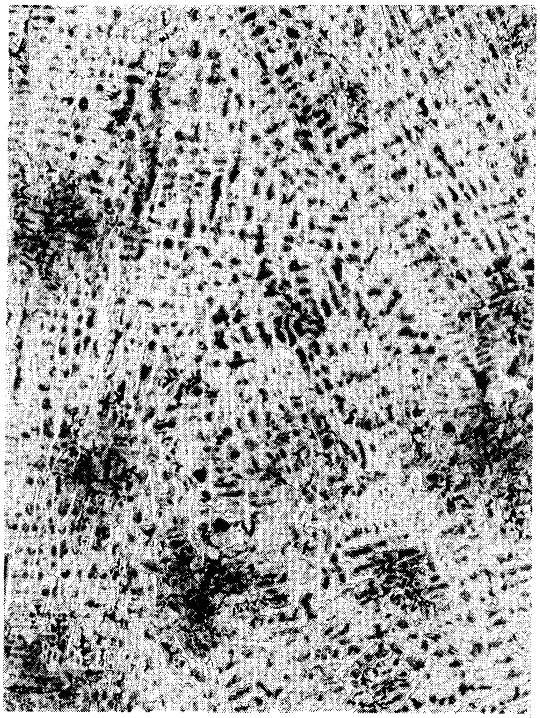


No Alloy - Normalized & Drawn
Pearlite Matrix - 241 BHN



Ni-Cr Alloy
Austenite Matrix - 170 BHN

Figure 9. Typical Microstructures of Nodular Iron.



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500X Etched

Figure 10. Microstructure of Alloyed Controlled Chill Hardenable Cast Iron.

White Cast Iron

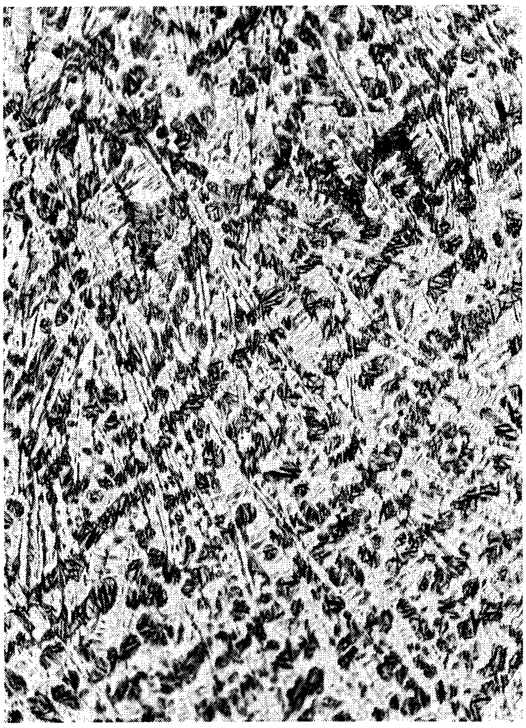
White cast iron is characterized by microstructure consisting of hard primary carbides with a matrix ranging from pearlite to a mixture of matrensite and austenite, depending on alloy composition. This material is hard and resistant to abrasion as a result of the structure, which has provided in it gross hardening due to the presence of massive carbides and, in the case of the martensitic type white irons, distribution of fine cementite particles in the matrix. White iron castings are generally brittle and must be supported in heavily loaded applications by tougher, stronger metals.

Because abrasion resistance is desired in white iron castings, carbon content is usually maintained at a relatively high level to provide large quantities of massive primary carbide. Metal for the castings can be melted in a cupola or in batch type air or electric furnaces and is adjusted with respect to composition such that a casting will have a white microstructure regardless of section size and cooling rate. Thus, thin section castings may have relatively high silicon content (up to 2%), while heavier section castings which cool more slowly are made from iron with a lower silicon content of perhaps .5%. Alloyed white irons can tolerate higher silicon content than unalloyed irons, because of the presence of carbide stabilizing alloys such as chromium, molybdenum, and vanadium.

Some castings requiring a specific combination of abrasive resistant properties and surface finish are produced from "grain iron". This material is predominantly of a white iron structure with a small quantity of primary graphite to produce the characteristic grained structure. This structure is similar fundamentally to that of the controlled chill hardenable iron, except that the degree of control is somewhat less precise than is exercised in the electric furnace melted controlled chill iron.

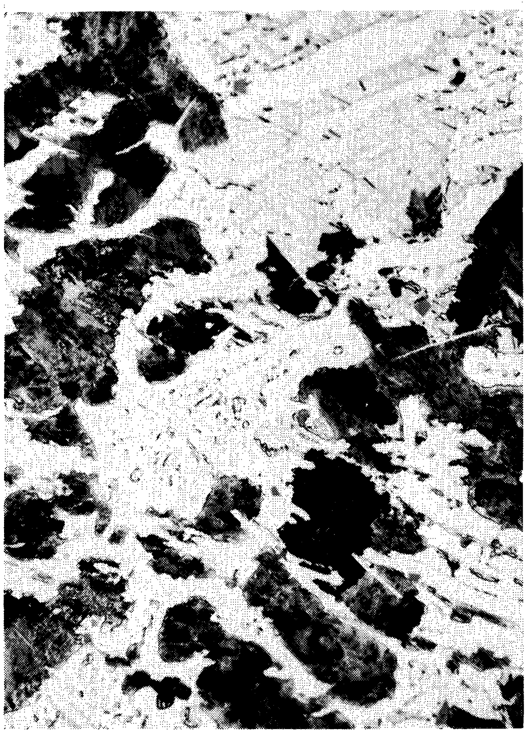
Figure 11 illustrates the range in microstructure obtainable in white cast irons, which have characteristic massive carbide and matrix constituents transformed from austenite during cooling. The upper right hand photograph shows an unalloyed iron with a pearlitic matrix. There is little chance for the formation of free ferrite in the white irons, even in unalloyed grades, since there is no nucleus in the structure upon which eutectoid cementite could deposit during cooling.

The two lower photographs in Figure 11 illustrate alloyed grades of white iron with matrices hardened by the presence of low temperature austenite. The lower left photograph shows a mixture of pearlite, bainite, and martensite in the matrix, while the lower right photograph shows a mixture of martensite and austenite. These materials exhibit better wear or abrasion resistance than an unalloyed white iron, since the hard primary cementite is further fortified by the presence of hard matrix structures.

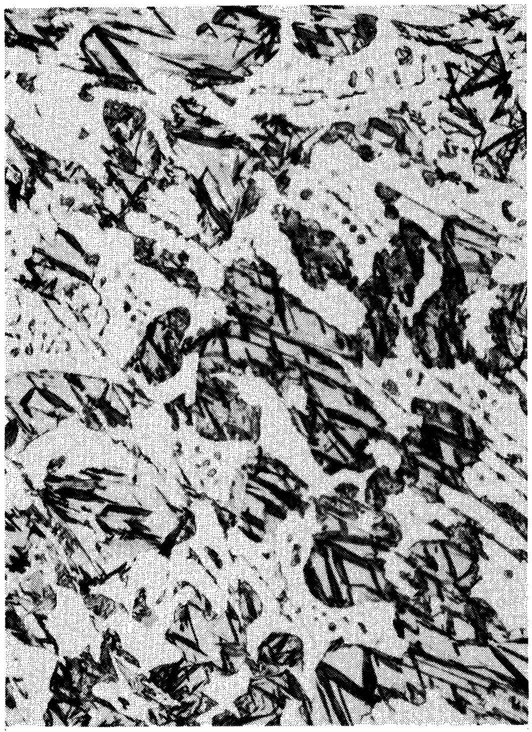


100X

No Alloy 500X
Pearlite & Cementite



Intermediate Alloy. 500X
Pearlite, Martensite & Cementite



High Alloy 500X
Martensite, Austenite & Cementite

Figure 11. Microstructures of Typical White Cast Irons.

Brinell hardnesses as high as 782 BHN have been developed in the martensitic alloyed white cast iron. Unalloyed irons of equal carbon content, approximately 3.5%, generally range in hardness from 555 - 600 BHN. The hardness developed is a function of both the quantity of primary carbide and the structure of the matrix, therefore, low carbon white irons with small quantities of primary carbide might develop hardnesses no greater than 300 BHN. Since resistance to abrasion is reasonably proportional to hardness, it is apparent that the higher carbon alloyed materials possess the best abrasion resistance, while low carbon alloyed white iron proves inferior.

SUMMARY

Modern high carbon ferrous metals provide a wide range of structures and properties for use in applications requiring resistance to surface damage. Graphitic materials are generally most suitable for lubricated wear conditions in which the natural lubricating characteristic of graphite and the presence of microvoids to contain liquid lubricant or to trap fine abrasive particles combine to provide high levels of wear resistance. A wide range of supporting mechanical properties is available through selection of the type of graphitic metal to be used. Minimum mechanical requirements can be met by gray cast iron, while higher requirements might call for the specification of pearlitic malleable, nodular iron, or malleable base spheroidal iron.

For conditions of severe abrasive wear, irons containing a carbidic constituent with alloyed matrix offer the greatest resistance. Under intermediate conditions, hardened graphitic iron or low alloyed white iron will be suitable.

Table 1 details the chemical composition ranges for the high carbon ferrous casting alloys discussed in this paper. The upper columns specify carbon, silicon, manganese, and sulfur contents which are inherent to and important parts of the constitution of all of the metals. Alloy contents are specified in the lower columns.

Table 2 details the specification properties for graphitic iron castings and demonstrates the wide range available to the design engineer.

TABLE 1

CHEMICAL COMPOSITIONS OF MODERN HIGH CARBON FERROUS CASTINGS*

Material	Graphite	C	Si	Mn	S
Unalloyed Gray Iron	Flake	2.80 - 3.50	1.80 - 2.50	0.60 - 1.20	0.15 Max.
Alloyed Gray Iron	Flake	2.80 - 3.50	1.50 - 2.50	0.60 - 1.20	0.12 Max.
Ni-Resist	Flake	2.00 - 3.00	1.50 - 2.50	0.60 - 1.50	0.10 Max.
Malleable Iron	Temper Carbon	2.20 - 2.60	1.00 - 1.60	0.35 - 0.50	0.15 Max.
Pearlitic Malleable Iron	Temper Carbon	2.20 - 2.60	1.00 - 1.60	0.35 - 0.50	0.15 Max.
Spher-A-Steel	Nodular	2.00 - 3.50	1.00 - 2.50	0.20 - 0.50	0.30 - 0.60
Nodular Iron	Nodular	3.00 - 4.00	1.80 - 3.00	0.20 - 0.60	0.02 Max.
Ductile Ni-Resist	Nodular	2.50 - 3.00	1.50 - 6.0	0.80 - 1.50	0.02 Max.
Controlled Chill Iron	Some Flake	2.80 - 3.20	1.90 - 2.50	0.7 - 1.50	0.15 Max.
Ni-Hard	None	3.00 - 3.50	.80 - 1.50	0.60 - 1.20	0.15 Max.

ALLOY CONTENTS

	Ni	Cr	Mo
Alloyed Gray Iron	.25 - 2.0	.15 - .75	.15 - .75
Ni-Resist	10 - 30	2.0 - 5.0	
Nodular Iron	.25 - 1.25		
Ductile Ni-Resist	18 - 32	0.5 - 5.5	
Controlled Chill Iron	.40 - 0.70	.80 - 1.20	.40 - .80
Ni-Hard	4.0 - 5.0	1.20 - 2.0	.15 - .40

*Where wide ranges in composition are given, composition is controlled by the foundry according to grade, section thickness and application.

TABLE 2

SPECIFICATION PROPERTIES FOR GRAPHITIC IRON CASTINGS

	Grade or Class	Tensile Strength	Yield Strength	Elongation	BHN	Modulus of Elasticity
Gray Iron*	110	20,000			143-187	$14\text{-}18\times10^6$
	111	30,000			170-223	
	120	35,000			187-241	
	121	40,000			202-255	
	122	45,000			217-269	
	60	60,000			228-285	
Malleable Iron	32510	50,000	32,500	10.0	121-143	$25\text{-}27\times10^6$
	35018	53,000	35,000	18.0	126-149	
Pearlitic Malleable Iron**	45007	65,000	45,000	7.0	163-207	$25\text{-}27\times10^6$
	53004	80,000	53,000	4.0	187-228	
	60003 (0)	80,000	60,000	3.0	197-241	
	50007	75,000	50,000	7.0	170-217	
	80002 (0)	100,000	80,000	2.0	241-269	
	90002 (0)	110,000	90,000	2.0	269-302	
Spher-A-Steel	65004	85,000	65,000	4.0	179-207	$25\text{-}27\times10^6$
	70003	90,000	70,000	3.0	207-241	
	80003 (0)	100,000	80,000	3.0	241-269	
	90002 (0)	110,000	90,000	2.0	269-302	
Nodular Iron**	60-45-10	60,000	45,000	10.0	143-207	$22\text{-}26\times10^6$
	80-60-03	80,000	60,000	3.0	207-269	
	100-70-03 (0)	100,000	70,000	3.0	241-302	
	120-90-02 (0)	120,000	90,000	2.0	269-388	
Ductile Ni-Resist		54,000 to 60,000	30,000 to 38,000	2.0 to 20.0	131-228	$13\text{-}19\times10^6$

*Gray iron does not have a precise yield point. Elongation is very low.
**Grades followed by (0) generally produced by oil quench and temper heat treatment.

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