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MATERIALS PROCESSING THRESHOLD REPORT
II. Use of Low Gravity for Cast Iron Process Development

FINAL REPORT
SPC 565

February 1980

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Prepared under
Contract NAS8-33518

Sponsored by
National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center
Alabama 35812

PROLOGUE

This volume is one of a series of Materials Processing Threshold Reports. These reports are designated to provide an abbreviated assessment of the state of the processing art in some materials technology areas and to identify any thresholds in increased material performance that have broad agency or industry utility. Particular attention is given to the special properties of space that might allow alteration of processing characteristics to provide increased material performance. The volumes presently available in the series are:

I. Semiconductor Crystals for Infrared Detectors

II. Use of Low Gravity for Cast Iron Process Development

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I. EXECUTIVE SUMMARY

This report has been prepared by System Planning Corporation (SPC) as part of the NASA's Materials Processing in Space (MPS) Program. SPC has assessed potential applications of a low gravity environment of interest to the commercial producers of cast iron. The purpose of the assessment is to determine whether low gravity conditions offer potential opportunities to these producers for improving cast iron properties and expanding the use of cast irons. Although the assessment has necessarily been limited to the gray and nodular types of iron, the findings are basically applicable to all cast irons. The following paragraphs briefly describe the potential advantages that might accrue through low gravity experiments with cast irons.

Cast irons are important engineering materials used predominately in transportation, construction, and heavy industry. Their appeal to users can be attributed to a variety of unique properties and characteristics, but probably the two most important advantages are that they can be readily cast into intricate shapes and are relatively inexpensive compared to alternate material selections. If certain physical properties of cast irons could be improved through processing in low gravity, usage of these materials would undoubtedly be greatly expanded. In the long run, cast irons, which are fabricated mostly with recycled stock, might be substituted for other materials requiring important natural resources. For instance, U.S. production of nodular cast irons has grown since commercial introduction in the early 1950s to about 3 million-tons per year, in part due to the new nodular graphite shape that made available physical properties in cast irons that had been attainable previously only with more expensive steels.

Cast irons are uniquely suitable for investigation of melting behavior and solidification mechanisms in a low gravity environment because of the broad difference in density of their compositional constituents. Certain characteristic physical properties result from what happens during solidification of castings; in turn, what happens during solidification under normal gravity conditions is strongly dependent on the force of gravity on the melt. By studying melting and solidification of cast irons under low gravity conditions, cast structures might be modified or process controls identified to provide desirable changes in physical properties. Those findings might then be adopted as modifications to current processing technologies under normal gravity conditions to enhance cast iron properties or to provide new engineering materials.

In production of most cast products, the most troublesome problem areas that strongly influence physical properties are chemical and constitutional heterogeneities and unsoundness in castings. These problems are strongly influenced by the interplay of density and constitutional properties during solidification and cooling of the castings. Cast irons are particularly sensitive in this respect because irons are complex alloys chemically and their melt constituents have widely varying densities. For example, when cast irons solidify, wide ranges of carbon and alloying compositions exist in the precipitating melt constituents. These differences in the melt often result in variable compositions and densities in the final castings, since some of the original as-precipitated heterogeneities are not interdiffused by the time the castings are fully solidified and cooled to room temperature. The high melting points of irons and allotropic transformations during cooling also create problems that contribute to these heterogeneities. Thus, iron castings normally have considerable heterogeneities in chemical composition and phase constituents that contribute to nonuniformities in mechanical properties and to low property values.

Cast irons, unlike most steels, contain part of their carbon as a free graphite constituent. The shape and size of the graphite constituent are difficult to control within specific desired ranges. In addition, when the relatively light graphite and heavy metal constituents are present in a melt, some mass stratification is to be expected due to the effect of gravity. With constituents of widely varying densities that have heterogeneities and with variable distribution, shape, and size of graphite, uniform physical properties are difficult to achieve.

Soundness of cast structures is also of paramount importance to service life in many applications. Here again, some of the problems in achieving sound castings can be attributed to the presence of constituents with widely varying densities (e.g., evolving gas bubbles and metal) and to chemical heterogeneities. Constituents of lower densities tend to float, and, if they are also of higher melting points, will solidify last. The result is lack of chemical uniformity, unsound areas, and unpredictable physical properties such as hardness and strength.

The variable densities of constituents contribute to the problems described above, and this is why the low gravity environment offers exceptional opportunities for experimentations. For instance, low gravity processing will be useful in examining nucleation and growth mechanisms during solidification since it will allow the important density variable to be isolated. In addition, containerless processing and rapid cooling during solidification could also be demonstrated in the MPS program and also provide valuable data concerning nucleation and growth. Such experiments should contribute to a fuller understanding of casting problems and lead to improvements in the physical properties of cast irons.

Improvements in mechanical strength properties, particularly higher fatigue strength, would undoubtedly find much favor among commercial producers and users of cast irons. Presently, 90 percent of material failures result from repeated use. Fatigue strengths for plain gray irons are about one-fourth to one-third of those for comparable grades of wrought steels. Generally, fatigue strengths of plain nodular irons are less than those of wrought plate steels of plain carbon compositions. Present levels of both fatigue and tensile strengths in gray and nodular cast irons are constrained at least in part by metallurgical solidification phenomena that are attributable to differences in density of the constituents in the melt. Studies in low gravity environments will provide an opportunity to learn whether property levels can be raised above the present constraints by lessening tne influence of density in the solidification process. If gray iron properties can be improved, this material can compete with some grades of cast and wrought steels and nodular irons. If the properties of nodular iron can be improved, these irons could be substituted for certain alloy and higher strength steels. In either case, an expanded market is foreseen for cast iron products that have greater strength properties than those achievable today.

An important consideration in planning a program for melting and solidification of gray and nodular irons under low gravity is that only scoping experiments be included initially. These experiments should encompass a broad view of the solidification process, including wide ranges of composition and cooling conditions, and should include one-for-one comparisons under both normal and low gravity conditions. The major objective at this point should be to determine if low gravity and containerless processing influence basic characteristics of the phase constituents and heterogeneities of the structures obtained under normal gravity conditions. These results will then point to logical directions for advanced experiments. If early exploratory experiments were aimed prematurely at commercial applications, the risk of program failure would be greater because the metallurgical principles related to solidification mechanisms and physical properties would never be revealed. A logical program sequence is (1) to reach an understanding of the solidification mechanisms and the influence of gravity on these, (2) to determine how to control these mechanisms, (3) to consider the total milieu (including economics, commercial applications, etc.) of the cast iron producers.

II. COMMERCIAL SIGNIFICANCE OF GRAY AND NODULAR IRONS

Within the broader group of cast irons, gray and nodular irons were selected for this limited assessment because both have widely varying structures and properties, are suitable for MPS experimentation, and are major industrial materials. The potential commercial significance of making improvements in these materials is discussed in this section, and the R&D aspects are reviewed in subsequent sections.

In 1977, about 12 million tons of gray iron and 2.7 million tons of nodular irons were produced and widely used in the United States, as shown in Table 1. Much of the appeal of these irons to the industrial sector is due to the fact that they are relatively inexpensive compared to other materials. This is attributable to the modest costs of both raw materials and of processing. For example, cast irons are usually made from pig iron, cast iron scrap, steel scrap, limestone, coke, and air. Gray iron is usually melted in a cupola and nodular iron in cupolas or in low-frequency induction or other electric furnaces. These iron production processes are all modest in operational costs compared to fully integrated steelmaking operations.

The underlying reason for the low production costs of gray and nodular irons compared to wrought steels can be illustrated in general terms by a brief comparison of alternative casting and wrought processes for production of automobile crankshafts. For the casting process alternative, nodular iron would be melted and cast to a near-final shape. A limited amount of machining would be performed, and the desired properties would probably be achieved through heat treatment. For the wrought process alternative, steel would be produced through manufacture of pig iron and subsequent melt refining (or, in a single step if recycled scrap is used exclusively) and would be cast as a large ingot. The ingot would next

TABLE 1. TYPICAL USES OF GRAY AND NODULAR CAST IRONS
(AFTER MATERIALS ENGINEERING [Ref. 1, pp. C2-C3])

GRAY IRONS

Vehicles and Engines

Engine blocks, heads, pistons, camshafts, crankshafts, exhaust manifolds, clutch plates and housings, oil pump bodies, gear boxes, brake drums, and flywheels.

Machinery

Machine tools, housings, frames, and supports; tooling for dies; and construction equipment for heavy compressors, gears, etc.

Other Uses

Pressure vessels, chemical processing equipment, furnace hardware, paper mill rolls, valve bodies, and hydraulic cylinders.

NODULAR IRONS

Vehicles and Engines

Crankshafts, camshafts, pistons, rocker arms, gears, pinions, gear housings, differential cases, steering knuckles, brake drums, cams, pumps, and exhaust manifolds.

Machinery

Gears, gear housings, cams, and slides.

Other Uses

Tractor shoes, valves, and fittings in steam equipment, paper mill and glass rolls, ship propellers, or salt water and caustic solution handling equipment. Heat-resistant grade used for furnace hardware, lead pots, and grate boxes.

be hot-worked mechanically and reduced to a large bloom shape much larger than the final desired shape. (The bloom is mechanically reduced to a rough billet shape somewhat larger than the final product.) Next, the billet is hot-forged into a crankshaft shape, approximately equivalent in size to the alternative as-cast shape. This intermediate shape is then machined and heat-treated--much the same as the finishing operations on the cast iron shape. Obviously, the iron casting processes can be performed at less expense than the more complicated wrought steel processes. On the other hand, a wider variety of physical properties can be offered through variations in wrought processing of steels than through casting iron directly to shape. For instance, steel wrought materials can be work-hardened during processing, and as-cast chemical heterogeneities in the ingot can be homogenized during subsequent working operations. In addition, properties can be enhanced selectively in wrought processes by establishing preferred orientations, or texturing, of the metallurgical structure.

If some of this flexibility in achieving desired properties could be provided in iron castings or if certain cast iron properties could be improved at reasonable cost, cast irons could surely displace steels in many commercial applications. For example, a simple change in graphite shape has previously resulted in a new class of irons--the nodular type. Within about 30 years, the market size of this product has grown to about one-fourth of the older gray iron market. This growth is due to the fact that nodular irons have tensile strengths three times greater than that of gray irons and exhibit ductility (not available with gray irons). As a result, nodular irons have been substituted for steels and malleable irons in numerous applications. A similar market penetration is within reach today if equivalent improvements could be made in the properties of any of the existing cast irons. Low gravity processing provides a research tool not previously available for investigating methods to bring about such property changes.

III. STRUCTURES OF GRAY AND NODULAR IRONS

When iron-carbon alloys are identified by the more commonly accepted names of steels or cast irons, almost everyone can probably associate experiences in their everyday lives with either or both groups of materials. Most technically trained persons could also probably relate professional experiences with these materials when the broad-based steel and iron classifications are categorized as specific compositions, properties, products, uses, etc. For instance, steels are generally considered to be alloys of iron that contain relatively lesser amounts of carbon than cast irons, and the carbon content of most cast irons, unlike steels, is present in the form of free graphite. In gray iron, this graphite appears as lenticular-shaped flakes when examined in microsections. In nodular iron, the graphite shape appears roughly circular in microsections.

Historically, metallurgical training in the properties of iron-carbon alloys has normally begun with the iron-rich side of the conventional iron-carbon phase diagram (Fig. 1). In the simplest view, most steels are in the carbon range below about 1.3 percent, although extremely favorable combinations of strength and ductility properties have been obtained recently in specially prepared steels containing carbon as high as 2 percent [Ref. 3]. Irons, including the gray and nodular types, are normally in the carbon range from 2 to 4.5 percent. Thus, the metallurgical properties of steels in this simple view are heavily dependent on the eutectoid reaction (point A, at 0.8 percent carbon, in Fig. 1) that results in mixtures of ferrite (alpha iron) and iron carbide at room temperature. Similarly, metallurgical properties of irons are heavily dependent on the eutectic reaction (point B, at 4.3 percent carbon, in Fig. 1). In this instance, the room temperature constituents are generally mixtures of ferrite, iron carbide, and graphite.

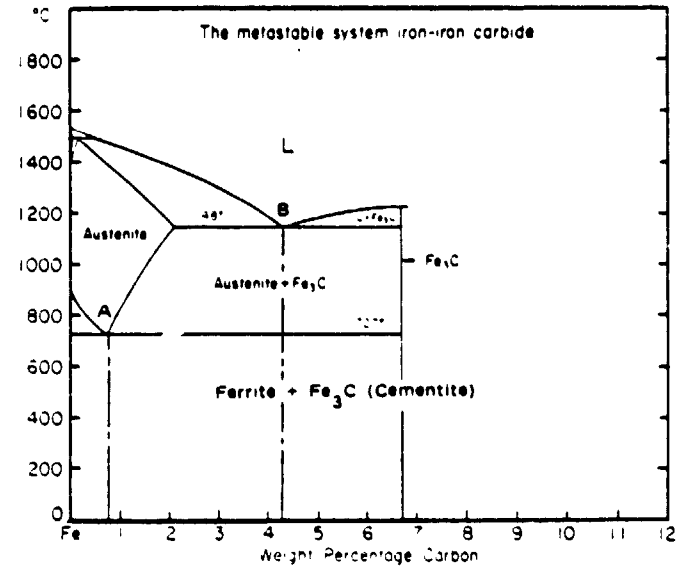


FIGURE 1. IRON-CARBON PHASE DIAGRAM--METASTABLE (Simplified Version, Modified After American Society for Metals [Ref. 2, p. 277])

Since the graphite phase constituent is not shown in Figure 1, a more detailed view of the metallurgical nature and behavior of iron-carbon alloys is warranted. Two additional basic concepts aid in explaining the presence of free graphite in most cast irons and the absence of this phase in most steels. The first concept concerns the persistence of varying amounts of the metastable iron carbide phase in essentially all commercial iron-carbon alloys, and the second concerns the differences in chemical composition between commercial iron-carbon alloys and the theoretical mixtures of pure iron and carbon represented in Figure 1.

In the more detailed phase diagram of Figure 2, alternative graphite (equilibrium) and carbide (metastable) carbon phases are shown, with some different solidification and transformation conditions for each. The dashed lines demonstrate the graphite eutectic point (C'), the eutectoid point (S'), and the limit of carbon solubility in gamma iron (line E'S'). These two points and the solubility line are at higher temperatures than the corresponding indications for the carbide phase, which are represented by the solid lines through points C, E, and S. The emergence of either graphite or carbide directly from the melt in the solidification of gray irons has been a conjectural matter among metallurgists for many decades and is still the subject of considerable study.

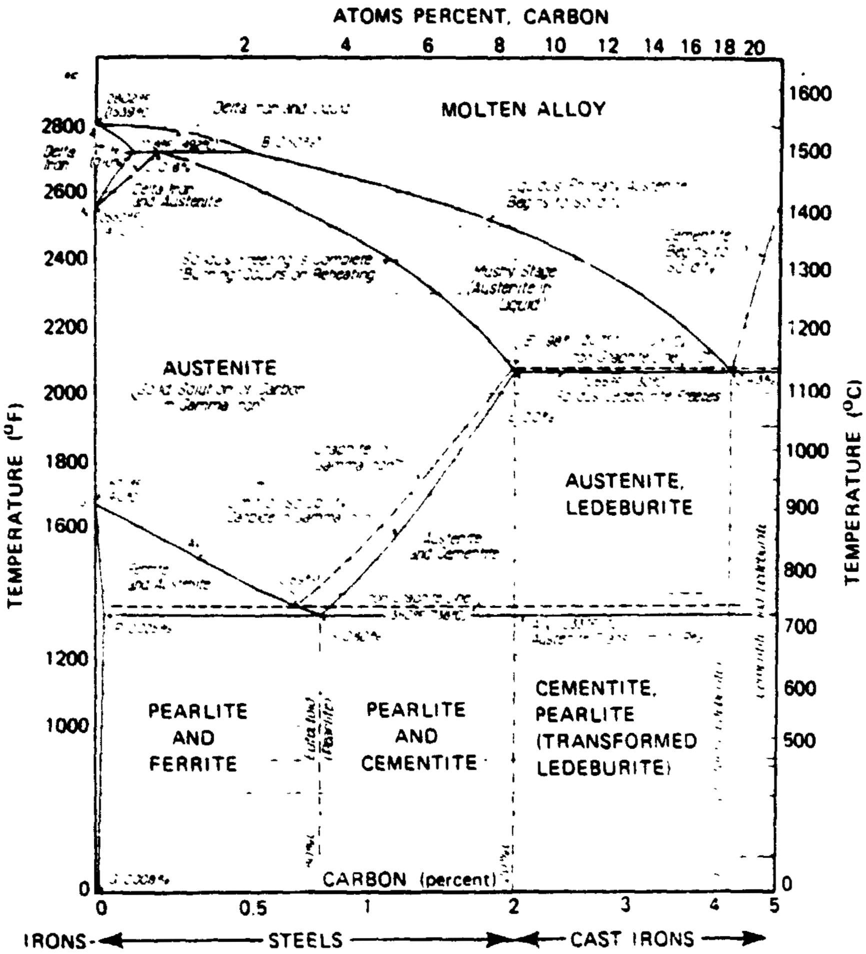


FIGURE 2. IRON-CARBON PHASE DIAGRAM--STABLE AND METASTABLE (Modified After H.T. Angus [Ref. 4, p. 2])

This idealized binary diagram (Fig. 2) showing the precise temperature levels for eutectic and eutectoid reactions does not account for the third major alloying ingredient in cast irons, silicon. The iron-carbon-silicon (Fe-C-Si) ternary phase diagram becomes much more complicated, as shown in Figure 3. A section of the binary phase diagram from Figure 2 is

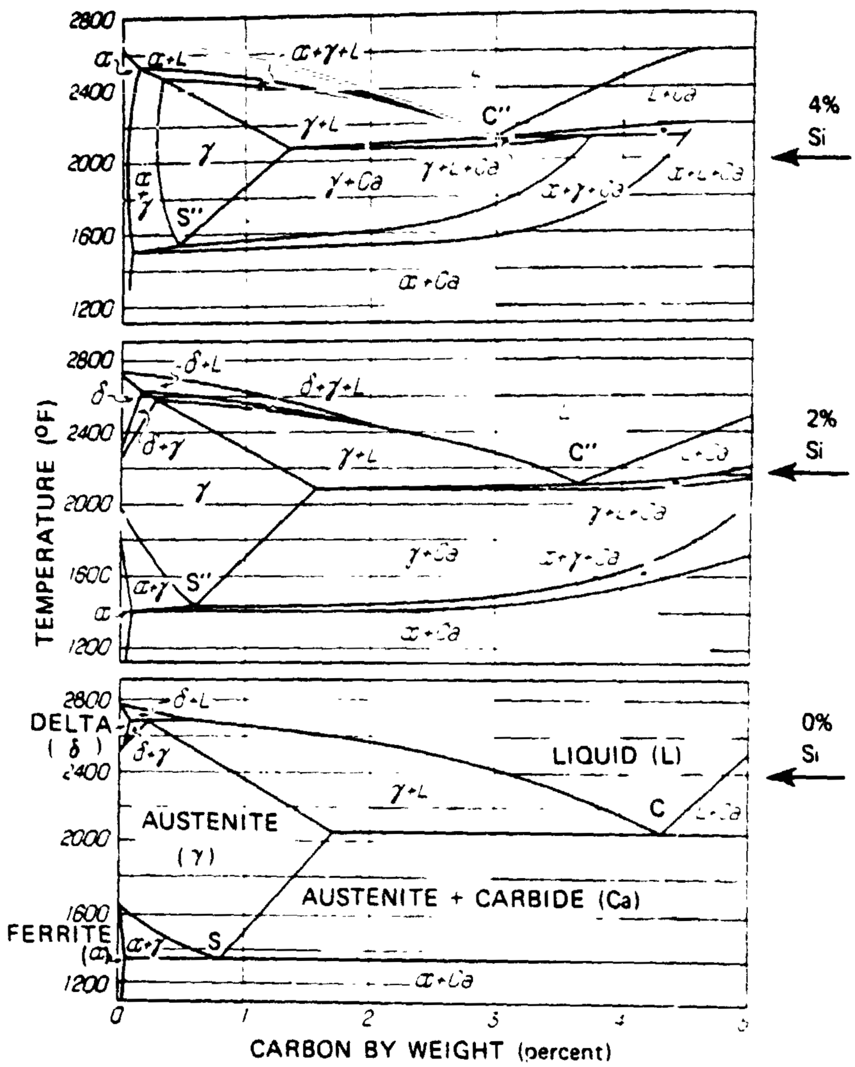


FIGURE 3. SECTIONS THROUGH THE IRON-CARBON-SILICON TERNARY PHASE DIAGRAM (Modified After A. Boyles [Ref. 5, p. 2])

reproduced at the bottom of Figure 3 for comparison. Above that section, identified as 0 percent Si, similar sections across the iron-carbon segment of the Fe-C-Si diagram are shown for 2 percent and 4 percent silicon, which are typical cast iron compositions. The previous eutectic (C) and eutectoid (S) points in the metastable carbide phase diagram are now displaced in carbon composition (points C" and S", respectively, and the prior specific temperature levels for the eutectic and eutectoid reactions are replaced by temperature bands that vary with both carbon and silicon compositions. Furthermore, in commercial practice, control of phase constituents becomes further complicated because of (1) the possible addition of other alloying elements, (2) the presence of residual elements inherent to the material, and (3) the use of heat treatments following casting solidification.

Although descriptions of cast iron structures can be provided through the use of simplified phase diagrams, such diagrams do not suffice to account for actual physical characteristics and behavior. For example, the phase diagrams indicate very little about the graphite constituent in cast irons. As shown in Figure 4, graphite may appear in various forms. The flake type shown as Form I is the idealized characteristic form for gray irons. Unfortunately, this idealized distribution of flakes is not universally achieved in commercial gray iron castings because of uncontrolled conditions in melting, casting, or other processing operations. Several flake distributions have been classified as shown in Figure 5--where Type A is the preferred distribution.

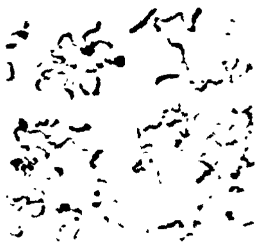
When the microstructure of gray irons is shown in the etched condition, the details of the matrix areas in Figure 5 are revealed. In a typical case, the structure appears as shown in Figure 6, where coarse graphite flakes are surrounded by a matrix of pearlite. Pearlite consists of alternate lamellae of ferrite (light) and iron carbide (dark) at the eutectoid composition (point A, Fig. 1). Thus, the planar microstructural form of gray iron typically consists of nonmetallic graphite flakes embedded within a matrix of metallic ferrite and intermetallic iron carbide. Depending on the chemical composition and processing of individual gray irons, the

x 100

Form I Flake graphite

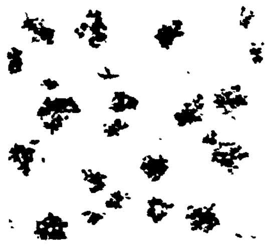
x 100

Form II Crab form graphite



x 100

Form III Quasi flake graphite

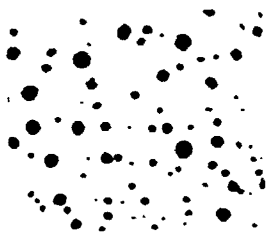


x 100

Form IV Aggregate or temper carbon

x 100

Form V Irregular or "open" type nodules



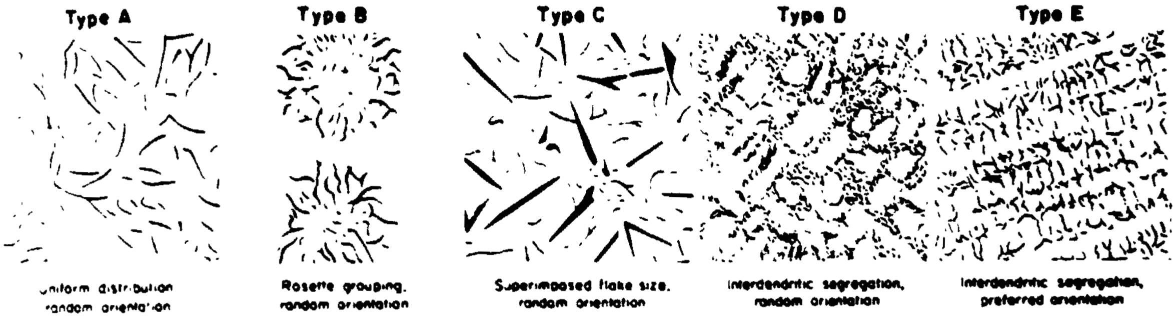
x 100

Form VI Nodular or spheroidal graphite

SOURCE: Reference 4, p. 8.

FIGURE 4. GRAPHIC TYPES OR FORMS FOR CAST IRONS

matrix may be pearlite (as shown in Fig. 6), ferritic, or a mixture of free ferrite and pearlite.



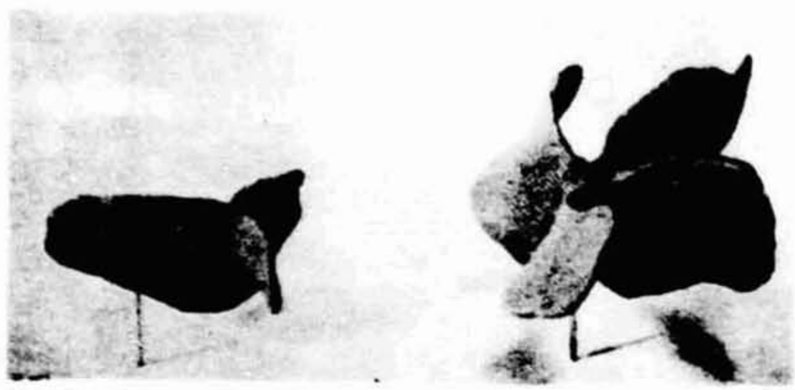
SOURCE: Reference 6, p. 351

FIGURE 5. CLASSIFICATIONS OF GRAPHITIC FLAKE MICROSTRUCTURES IN GRAY IRONS (At magnification of 100X, but reduced to one-third size for reoroduction).

SOURCE: Reference 2, p. 90.

FIGURE 6. TYPICAL GRAY IRON MICROSTRUCTURE AFTER ETCHING (Etched in 4 percent picral; 300X magnification).

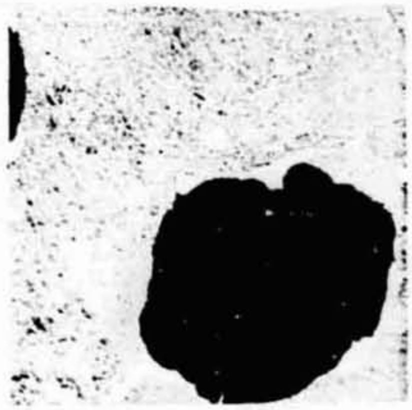
Although the lenticular or flake shape of the graphite is typical for the planar view of the microstructure, the three-dimensional form is somewhat more complex and is sometimes referred to as a whorl. Two models of whorls, constructed from a continuum of microstructural views, are shown in Figure 7. These macrostructural views undoubtedly provide more insight than do the microstructures about the influence of graphitic structure on mechanical properties of cast irons. Essentially, gray iron can be envisioned in the three-dimensional form as a rigid, continuous structure (the matrix of ferrite and iron carbide) that is punctured with whorl-shaped cavities located randomly within the matrix. These cavities, in turn, are filled with a granular or powdery form of graphite.



SOURCE: Reference 5, p. 46.

FIGURE 7. MODELS OF GRAPHITE WHORLS, REPRESENTATIVE OF THE TYPE A FLAKE STRUCTURE OF FIGURE 5 (150X magnification)

The microstructures and macrostructure of nodular iron are much the same as those for gray iron except that the graphite flakes and whorls in the latter material appear in the former as rounded shapes, or nodules, in the three-dimensional view. The microstructural view in this case can be envisioned as a block of Swiss cheese with the holes filled with a foreign substance. In this case, the "cheese" matrix is ferrite and iron carbide, and the "holes" are filled with graphite. The nodules are represented by Form VI in Figure 4, and a typical etched microstructure of nodular iron is shown in Figure 8. In this view, the full and partial planar surfaces of two graphite nodules are shown, surrounded by the pearlite lamellae of ferrite and iron carbide. The smallish light-colored regions around the nodules are areas of free ferrite.



SOURCE: Reference 2, p. 89.

FIGURE 8. TYPICAL NODULAR IRON MICROSTRUCTURE AFTER ETCHING (Etched in 4 percent picral; 300X magnification).

Just as in the case of gray irons, the desired graphitic shape is not always obtained because of various uncontrolled composition or processing factors. Of the five types of graphite shapes shown in Figure 9, No. 1 is preferred, and some amounts of Nos. 2 and 3 are also considered to be generally acceptable in achieving the desired mechanical properties for nodular iron. Obviously, with the graphite types shown as Nos. 4 and 5 (in Fig. 9), the material tends to appear more like a gray iron and exhibits considerably different mechanical properties than those expected for nodular iron.

The chemical composition of nodular iron is much the same as that of gray iron, except that an inoculation agent is added to the molten iron to provide the characteristic nodular rather than flake forms of graphite. Various inoculating agents have been used, including mischmetal, magnesium alloys, ferrosilicons, calcium-silicon alloys, etc. These, of course, remain to some degree as a chemical constituent in the final nodular iron product.

SOURCE: Reference 6, p. 393.

FIGURE 9. CLASSIFICATIONS OF GRAPHITIC MICROSTRUCTURES IN NODULAR IRON (100X magnification).

IV. CHEMICAL AND PHYSICAL PROPERTIES OF GRAY AND NODULAR IRONS

In addition to the basic elemental ingredients of gray and nodular irons (iron, carbon, and silicon), plain irons in both of these groups usually contain some residual manganese (<1.0 percent) and small amounts of sulfur and phosphorus. Other alloying elements are sometimes added to obtain improvements in specific properties; those most commonly used are aluminum, copper, chromium, molybdenum, nickel, and vanadium.

Selected chemical and physical requirements and properties for commercial grades of irons within these two groups are presented in Tables 2 and 3. Data in these tables show both the similarities in chemical compositions of the two groups and the differences in physical properties resulting from different phase characteristics. Because of differences in microstructure and macrostructure of gray and nodular irons, some inferences can be made about comparative properties. For example, gray irons have less tensile strength than either nodular irons or steels. In gray irons, the continuous matrix structure is filled with relatively sharp stress raisers--the graphite whorls (see Fig. 7). In nodular irons, the graphite shapes are rounded and are not as likely to act as stress raisers. In steels, the matrix is characteristically void-free except for a few relatively small-size nonmetallic inclusions. As shown in Table 2, ultimate tensile strength in certain plain gray irons is specified typically in a range from about 20,000 to 40,000 psi. These same values for some nodular irons range from about 60,000 to 100,000 psi, as shown in Table 3. For comparison, these values would normally range from about 65,000 to 105,000 psi for cast plain carbon steels [Ref. 1, p. C8].

TABLE 2. TYPICAL PROPERTIES FOR SELECTED GRAY IRONS (AFTER MATERIALS ENGINEERING [Ref. 1, pp. C2-C3])

	ASTM[a] A-48 Class or Grade 20, 25	ASTM[a] A-48 Class or Grade 30, 35
Mechanical Properties		
Tensile Modulus of Elasticity, 10^6 psi	9.6-14.8	13-17.2
Ultimate Tensile Strength, 1,000 psi	20-30	30-40
Ultimate Compression Strength, 1,000 psi	80-100	109-125
Fatigue Strength, 1,000 psi		
Unnotched	9.5-15	13.7-17.5
Notched	9.5	13.5
Impact Strengths, foot-pound		
Izod, Unnotched	21-22	23-25

Composition, Percent	Compositions vary with specification; major elements include up to 3.75 C, up to 2.4 Si, up to 0.9 manganese, plus small amounts of sulfur and phosphorus. Standard grades may also contain up to 5 Ni, up to 1.25 Cr, up to 1 Mo, and up to 1.7 Cu. Nickel alloyed grades contain up to 0.7 Mo and up to 6 Cr.
Corrosion and Oxidation Resistance	Somewhat more corrosion resistant than plain carbon steels. Rate of attack unlikely to exceed 5 mile/year in most severe industrial atmospheres. Hard, fresh waters not particularly corrosive; soft waters may cause some attack. Waste waters corrosive especially if containing chlorides or acids. Seawater much more aggressive, but even unalloyed grades may provide adequate resistance in still, unpolluted, well-aerated seawater. Alloying with Cu, Cr, Ni reduces seawater attack. In soils, pearlitic grades slightly more resistant than ferritic grades. Unalloyed gray irons have poor resistance to dilute and intermediate concentrations of common mineral acids but satisfactory resistance to low velocity concentrated acids such as sulfuric, nitric, chromic, and crude phosphoric. Resistant to dilute alkalies at any temperature, but hot solutions over 30 percent concentration will attack. Useful oxidation resistance to about 1,000°F; low alloy chromium-bearing grades useful for extended periods up to 1,200°F.
Damping Capacity	Excellent; exceeds that of most structural materials.

[a]American Society for Testing and Materials.

TABLE 3. TYPICAL PROPERTIES FOR SELECTED NODULAR IRONS (AFTER MATERIALS ENGINEERING [Ref. 1, pp. C2-C3])

	ASTM[a] A-48 Class or Grade 60-40-18 or 60-45-12	80-55-06[b]
Mechanical Properties		
Tensile Modulus of Elasticity, 10^6 psi	23-25	23-25
Ultimate Tensile Strength, 1,000 psi	60-80	80-100
Ultimate Compression Strength, 1,000 psi	56[c]	88[c]
Fatigue Strength, 1,000 psi		
Unnotched	30.5	39-40
Notched	18-23	21-24
Impact Strength, foot-pound		
Izod, Unnotched	120	120
Composition, Percent	T.C. 3.4-4, Mn 0.2-0.6, P 0.06-0.08 Ni 0-1, Mg 0.02-0.07	T.C. 2.3-3.8, Si 2-3, Mn 0.2-0.5, P 0.06-0.08, Ni 0-1, Mg 0.02-0.07
Corrosion and Oxidation Resistance	Corrosion resistance generally similar to gray irons. Machining tends to increase atmospheric corrosion resistance slightly. In soils, ductile irons less sensitive than gray irons to strength loss due to corrosion. Prone to stress corrosion cracking in highly alkaline solutions. Standard grades have good oxidation resistance to 1,200°F; heat resistant grade (5-6 Si) has useful oxidation resistance up to about 1,650°F.	
Damping Capacity	Good, but not as good as gray or malleable irons.	

[a]American Society for Testing and Materials

[b]Higher mechanical properties are obtained by control of casting and heat treatment processes variables.

[c]Yield strength

Graphite plays a different role under compression loading, and enhances this strength in cast irons--particularly in gray irons. Graphite is essentially incompressible, and the matrix around the flake areas also yields locally to forestall fracture of the total section. Consequently, compression loads of gray irons can be as high as for steels with 3 to 4 times the tensile strength of the irons. In addition, ultimate compression strengths of gray irons may be as high as, or higher than, those exhibited by nodular irons that have ultimate tensile strengths of 3 to 5 times those of the gray irons.

The endurance limit, or fatigue strength, of individual cast irons is another property of interest in any comparisons with steels. Normally, the ratio of fatigue strength to ultimate tensile strength for gray irons is about 0.35 to 0.45, but this ratio may be higher for nodular irons and steels. In addition, gray iron has another inherent advantage in uses where surface scratches and defects pose problems because it is relatively insensitive to the effects of notches and rough surfaces, as shown by values given for notched and unnotched fatigue strengths in Table 2. The addition of a deliberately produced notch does not greatly affect the properties of a material that is already "notched" by the internal graphite flakes.

V. PROBLEMS WITH CAST IRONS

A basic problem limiting the increased use of gray iron is its relative weakness under tensile stress and its lack of ductility. Nodular iron is somewhat better in those respects but is still wanting when compared to many grades of steel. These limitations are generally acknowledged to result from the characteristic cast iron structures (as discussed in Sec. IV) and from chemical and constitutional heterogeneities and unsound regions in castings. As a result of these perceived problems, iron castings are often thought to be "weak" and less desirable than wrought or "worked" materials. This situation, as reflected by problems encountered in production of iron castings, is examined in this section; changes in the physical properties of gray and nodular irons that might reduce the intensity of production problems are discussed in the section following.

Chemical heterogeneities in castings are usually traceable to variations in chemical compositions within the melt, density differences among constituents, certain thermal effects, and specific solidification mechanisms. Since all of these factors are active more or less simultaneously and are to a great degree interdependent of each other during melt solidification, isolation of the effect of each factor is desirable in understanding solidification behavior. Low gravity processing offers one step toward such isolation by eliminating the influence of density differentials in the melt. Also, containerless processing is feasible in low gravity experiments, and this feature eliminates the influence of container walls on the nucleation and growth mechanisms that are active during melt solidification.

A. COMPOSITIONAL PROBLEMS

An important concept in understanding solidification behavior is that chemical compositions of the liquid and solid phases solidifying in an iron casting are continually changing. These changes obviously result in heterogeneities in the as-cast metal and in weaknesses and inconsistencies in its mechanical properties. Such compositional changes can be demonstrated with the simplified version of the metastable binary phase diagram shown in Figure 10. For example, assume that a theoretical

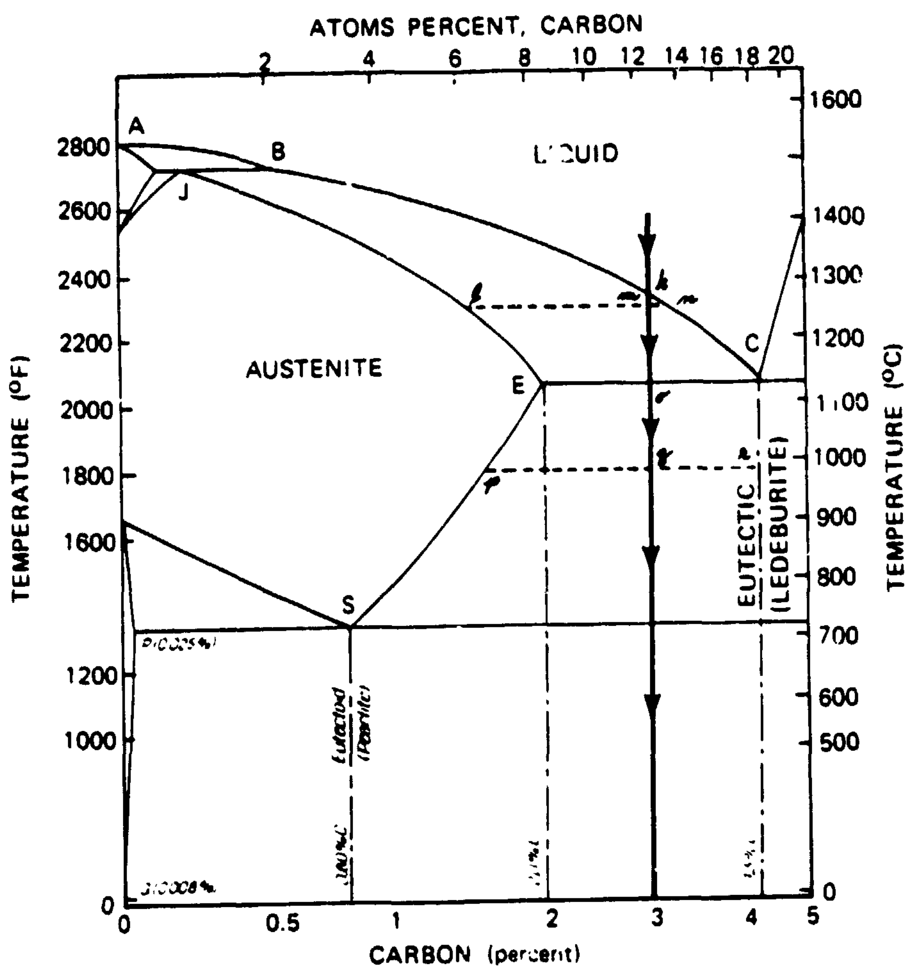


FIGURE 10. SIMPLIFICATION OF IRON-CARBON PHASE DIAGRAM--METASTABLE (Modified After H. T. Angus [Ref. 4, p. 2])

iron-carbon alloy of 3-percent carbon is cooled from the liquid range (above 2,315°F). Upon reaching the liquidus curve, at point k (2,315°F), solidification begins. When the temperature has been decreased to 2,300°F at point m, a small amount [(n-m) ÷ (n-ℓ)] of the melt has been transformed to austenite. This austenite has a carbon content of 1.2 percent (point ℓ), and the liquid phase remaining has a carbon content of 3.1 percent (point n). As cooling continues to the eutectic temperature, at line EσC, the carbon content of the austenite changes continuously along line ℓE and the carbon content of the remaining liquid increases continuously along line nC. In addition, the portions of separated austenite and remaining liquid change until just above the eutectic line, where about 40 to 45 percent [(σ-E) ÷ (C-E)] remains as liquid. At the eutectic temperature, the remaining liquid transforms isothermally upon arrest. The solidified eutectic (ledeburite) and austenite remain upon cooling below the eutectic temperature.

As cooling proceeds downward from the eutectic temperature (line EσC) to the eutectoid temperature (the horizontal line through point S), solubility of carbon in austenite decreases along line ES and the amount of ledeburite increases relative to austenite. At point q, as an example, the relative portions of austenite and ledeburite would be [(r-q) ÷ (r-p)] and [(q-p) ÷ (r-p)], respectively. Below the eutectoid temperature, ledeburite is not considered to be stable, and pearlite and cementite would be expected to be present at room temperature in this theoretical pure binary alloy. In actual practice with commercial cast irons, some combination of pearlite, ferrite, cementite, and graphite is likely to be present at room temperature.

The lesson to be learned from this somewhat onerous downward excursion through the phase diagram is that both the chemical compositions within phases, the phase constituents themselves, and the relative portions of each are continuously changing. In commercial practice, the rate of cooling and the alloying ingredients have major influences on the degree to which the heterogeneities are interdiffused by the time room temperature is reached. Certainly, a wide range of localized carbon compositions is not unexpected for as-cast structures--particularly in a small casting that has been cooled fairly rapidly. Such variations in carbon composition must undoubtedly have a significant influence on the mechanical properties of materials used in the as-cast condition.

The rather simple illustration for a binary iron-carbon alloy is further complicated in iron castings by the presence of residual elements, such as sulfur and manganese, and alloying elements. These all form compounds or alloys of various compositions, densities, and melting temperatures. Each of these chemical elements and their chemical and physical properties contribute to additional chemical heterogeneity within the cast structures.

B. DENSITY PROBLEMS

The separation of solid phases from the liquid and the subsequent growth are also important to discussions of heterogeneities in castings. Two views of the formation of initial graphitic material in gray irons are presented in Figure 11 for hypoeutectic[1] and hypereutectic[2] compositions. In the former case, this author postulates that metal separates from the melt first. Graphite flakes then nucleate and grow within the solidified dendrites and eutectic cells, and a heavier solid metal is floating in liquid metal. In Figure 12, an as-cast microstructure is shown that reveals the characteristic dendritic pattern developed in the metal phase during the original solidification.[3] For the hypereutectic irons the author postulates that some graphite (identified as kish) separates directly from the melt and that the austenite grows as cells during the eutectic arrest. In this case, a light graphite material is floating in a heavier liquid. Although the subject of graphite versus carbon nucleation and growth is conjectural, these two views of the subject probably

[1]Carbon content less than 4.3 percent (eutectic point C) in Figure 2.

[2]Carbon content greater than 4.3 percent (eutectic point C) in Figure 2.

[3]Graphite flakes are not evident in this view, since this is a "white" iron--without graphite.

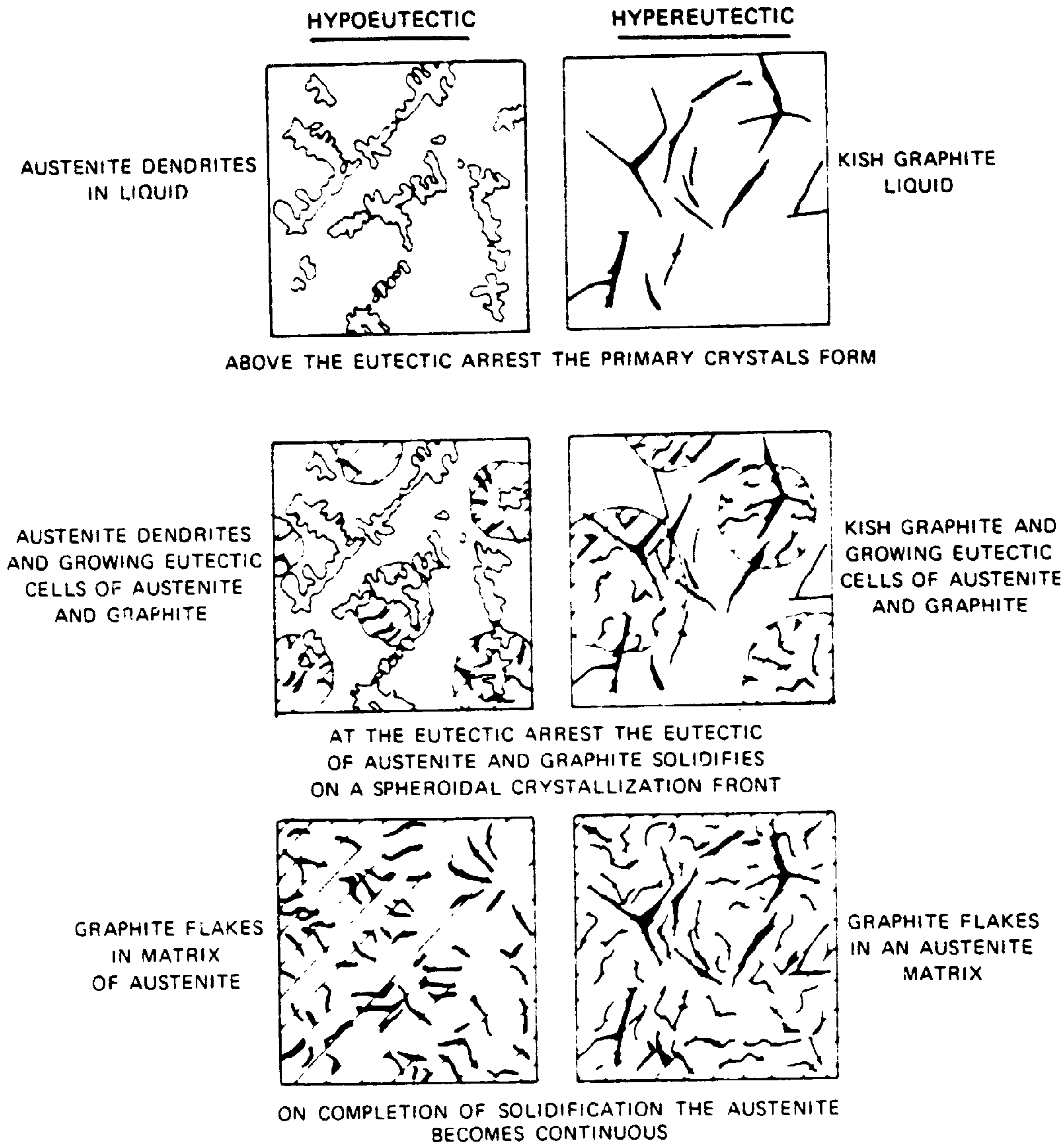
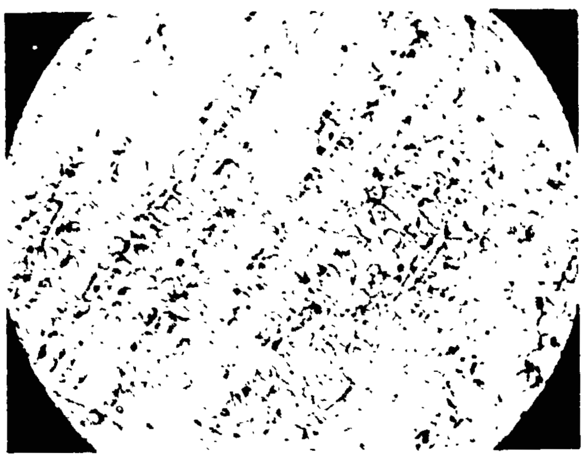


FIGURE 11. SEPARATION OF SOLID PHASES FROM THE MELT (Modified After H. T. Angus [Ref. 4, p. 6])

have received as much of a consensus as any other alternative theories. The important issues are that (1) nucleation and growth mechanisms of the various phases may be different for different compositions, (2) density may play a different role in each case, and (3) complete agreement has not been reached on the solidification mechanisms--particularly in regard to the formation of graphite.

Other density differentials in the melt and the solidified castings are to be expected. For instance, sulfur compounds are usually relatively light, and many alloying elements are heavy; thus, these materials are expected to segregate to some degree in the melt. Density gradients within solidified castings are also expected because of differences in melting points of melt constituents. Higher melting constituents tend to segregate in the regions of final solidification.



SOURCE Reference 4, p 24

FIGURE 12. EVIDENCE OF ORIGINAL DENDRITIC STRUCTURE REMAINS IN AN AS-CAST PEARLITIC WHITE IRON (Etched in 4 percent picral, 66X)

In addition to these sedimentation effects, another factor further complicates solidification behavior and imposes an influence on casting structures and on the resultant properties. This is buoyancy-driven (or gravity-driven) convection, which has already been recognized in NASA's program [Ref. 7]. Gravity-driven convection is caused by differences in density that result from even slight differences in temperature within the melt. As temperatures increase, materials tend to expand and become lighter per unit volume. These density differences, under the influence of gravity, result in a "convection flow" in liquid phases. This flow will contribute, along with the many other solidification phenomena, to chemical heterogeneities in the melt and final casting.

C. CASTING SOUNDNESS PROBLEMS

Nucleation and growth of the solid metal phases from the liquid phase is an important concept of solidification--particularly when considering the solidification of fairly heavy castings or ingots. In one simplified view, three solidification zones exist for nucleation and growth from the melt, as shown in Figure 13. The surface, or skin, freezes rapidly in the form of small equiaxed grains. In this initial solidification, nucleation predominates over growth. This solidification phase is followed by dendritic, or columnar, growth inward from the surface toward the center of the melt. In this case, the growth mechanism predominates over nucleation. The central portion of the melt solidifies last, from bottom to top, as an equiaxed structure--but with a coarser crystalline structure than in the original surface solidification area. Furthermore, during the columnar and final equiaxed solidifications, the less soluble chemical impurities remain molten and result in a graduated chemical segregation. The most persistent forms will migrate to the upper central section (see Fig. 13) of the casting or ingot and are often solidified there or entrapped as non-metallics. Thus, heterogeneities or voids are postulated during solidification of the melts.

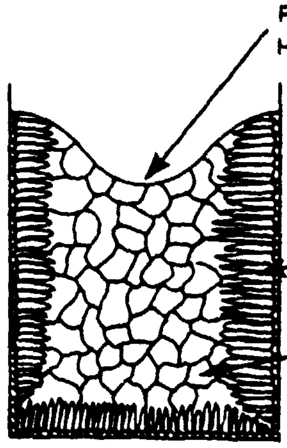


FIGURE 13. SCHEMATIC VIEW OF NUCLEATION AND STRUCTURE GROWTH IN HEAVY SECTIONS (Modified After R. E. Smallman [Ref. 8])

Soundness of castings can also be dependent on bubbles of entrained gases and allotropic transformations during cooling (coupled with the variable shrinkage characteristic of each allotropic phase). Both of these conditions may contribute to the chronic problem of voids in castings. The elimination of gravity and of container surfaces around the melt will provide excellent opportunities to study formation of such voids in cast irons.

Directionally induced solidification is a control normally used in the design of both castings and their mold containers to cause movement of the liquid-solid interface in a desired direction during solidification. This is often employed to enhance some specific property of the cast product, but it may also contribute to casting problems. The typical chronic problems resulting from poor control of directional solidification are soft or hard spots and shrinkage voids. Studies of nucleation and growth and inter-diffusion of phases under rapid cooling in a confined radius dimension in NASA's program could be extremely useful in the analysis of these problem areas in production of iron castings.

D. SUMMATION

The foregoing descriptions of three problem areas are considered to be typical of those encountered in the foundry in the production of homogeneous and sound iron castings. The solidification mechanisms described in those illustrations are also considered to be typical of the many factors that influence the physical properties of gray and nodular iron products. In summation, the following points have been established:

- The mechanisms resulting in formation of the chemical phase constituents in cast irons are complex and not adequately described by simple phase diagrams.
- The mechanisms resulting in the formation of the stable graphite phase are not fully understood and may be different for cast irons of different compositions.
- Chemical heterogeneities within individual phase constituents and in interdistribution of the constituents are to be expected in as-cast structures.
- Nucleation and growth mechanisms extant in separation of the solid phases from the liquid melt are dependent not only on chemical and density differences within the melt but also on controls and influences brought to bear from outside the melt. Rapid cooling methods are extremely useful in examining this aspect of the solidification process.
- Cast iron solidification mechanisms are worthy subjects for study in low-gravity environments because the elimination of gravity and container surfaces is expected to impact significantly on nucleation and growth, macrochemical heterogeneity, and size and distribution of the microphases.
- Once these solidification mechanisms are understood, improved control of the solidification process is feasible and improved physical properties in gray and nodular irons are within the realm of reason.

VI. POTENTIAL RESULTS WITH LOW GRAVITY PROCESSING OF GRAY AND NODULAR IRONS

Low gravity processing experiments may contribute substantially to understanding cast iron solidification problems. Such experiments are expected to have measurable influences on the interdistribution, shape, and size of phase constituents in cast irons--including those characteristic of the graphitic phase. These influences, under proper controls, should provide opportunities in the commercial gray and nodular iron industries for producing more homogeneous castings with improved physical properties. The question addressed in this section is which physical properties are most important to attaining wider usage of these materials.

Since gray and nodular irons are used extensively in heavy industry and transportation, mechanical strength properties are of major importance. Most likely, improvements in tensile strength and ductility and impact and fatigue strengths would result in significant substitution of gray and nodular irons for other more expensive materials--particularly steels. A comparison of the typical properties for plain cast irons with those of low carbon wrought steels is shown in Table 4. The major differences between gray iron and nodular iron and low-carbon wrought steel are the absence of ductility and the relatively low strength values. Nodular iron, on the other hand, compares favorably with low carbon wrought steel except for ductility under tensile stress.

In the user's world, however, most service failures result from repeated use. Even though products may be purchased in compliance with specific tensile or other strength and ductility tests, the fatigue life is usually the determining factor in how long the product endures in service. If the gray iron fatigue strengths could be tripled or the nodular iron fatigue strengths increased 30 percent, these materials could compete with at least one class of steel. The market performance of nodular irons has

TABLE 4. PROPERTY IMPROVEMENTS FOR EXPANDING CAST IRON MARKETS

Tensile Properties[a]	Gray Iron	Nodular Iron	Low Carbon Wrought Steel
UTS (1,000 psi)	20 to 35	60 to 120	70 to 90
Percent Elongation	--	2 to 18	10 to 35
Impact Properties[a]			
IZOD, ft-lb	20 to 25	120	80 to 90
Fatigue Strength[a]			
Rotating Beam (1,000 psi)	10 to 15	30 to 50	40 to 50

[a]Minimum levels for typical "plain" grades.

already demonstrated how changes in properties of these same orders of magnitude resulted in substantial substitution of cast irons for steels.

Nodular iron property improvements resulted from a simple change in graphite shape, from flake to nodule. Experiments with low gravity processing of gray and nodular irons hopefully will lead to new process control measures for melt solidification that could provide more desirable distribution of phase constituents and improvements in casting homogeneity and soundness. Such improvements, in turn, hopefully will provide new market penetrations for new cast iron materials comparable to those already achieved with nodular irons.

VII. INITIAL LOW GRAVITY EXPERIMENTS

With considerable emphasis in NASA's program already placed on solidification processes [Ref. 7], gray and nodular irons are ideal materials for eventual extension of those early efforts into commercial engineering materials. These irons offer excellent opportunities for studying the effects of natural convection and sedimentation during solidification. In addition, separation of constituents from the melt that exhibit widely varying densities also offers a unique opportunity to study nucleation and growth mechanisms in hypoeutectic and hypereutectic compositions. The question addressed in this section is how the initial experiments should be planned to exploit these opportunities effectively.

The most logical plan is to perform initially a series of scoping experiments to determine what obvious influences low gravity and containerless melting might have on the solidification mechanisms and on the chemical heterogeneity and microstructures of both gray and nodular irons over a variety of compositional ranges. Nucleation and growth of both graphite and the other phase constituents should be of primary interest at this point. In addition to the variables associated with the type of cast iron and its chemical composition, cooling rates and other cooling conditions would be the primary variables used in experimental design. The major objective would be to determine the nature of the influence, if any, that low gravity processing has on solidification mechanisms. In later experiments, the degree of such influences could be investigated, and eventually applications to commercial processing could be considered.

One possibility, although not considered to be likely at this point, is that early results will offer no encouragement for influencing either cast iron solidification or properties through low gravity processing. In that case, an obvious alternative might be to eliminate these materials from NASA's MPS program. More likely, the early experiments will provide indications of more fruitful directions to be pursued in subsequent experiments. For that reason, the initial scoping studies should be planned to encompass broad views of the solidification process. At this point, the experimental objectives should be more attuned to learning whether low gravity processing shows any evidence of influencing a solidification mechanism or characteristic of a microconstituent than whether it will change physical properties of cast irons. The initial experiments should be exploratory only and should not be expected to have any bearing at this point on commercial processing. Once underlying principles have been uncovered, commercial applications will follow.

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FIGURES

TABLES