GRAVITY INDEPENDENT MACRO/MICRO-STRUCTURAL FEATURES: Lessons from Nickel-Iron Meteorites

P.Z. Budka, 2135 Morrow Avenue, Schenectady, NY 12309
J.R.M. Viertl, 1403 Clifton Park Road, Schenectady, NY 12309
S.V. Thamboo, 2444 Brookshire Dr., Schenectady, NY 12309
R.A. Schiffman R.S. Research, Barton, VT 05822

Abstract

Segregation during solidification plays a major role in determining metal alloy macro/microstructural features which, in turn determine fundamental material properties. Segregation control is a major area of industrial research in the production of, for example, large iron-nickel superalloy ingots, yet the understanding of alloying element behavior is incomplete. The microgravity environment offers an ideal opportunity to study the basic properties of segregation for purposes of determining the influence of gravity related phenomena. Nickel-iron meteorites can be viewed as iron-nickel alloys which solidified in a vacuum under microgravity conditions. Their macro/micro-structural features exhibit strikingly regular patterns over a range of compositions and processing conditions. As large microgravity research specimens, nickel-iron meteorites can, therefore, provide insights into fundamental segregation behavior. Gravity independent features include phase selection as evidenced by the close relationship between phases found in steels and those found in the nickel-iron meteorites: delta ferrite (kamacite), austenite (taenite), sulfides, carbides, graphite, and martensite. In contrast with earth alloys, the microgravity environment allowed the meteoritic phases to grow into large, three-dimensional crystalline structures. Thus, meteorites offer an ideal opportunity to study segregation for purposes of distinguishing among gravity independent, microgravity and earth gravity-related phenomena.

Introduction

Segregation during solidification plays a major role in determining metal alloy macro-/micro-structural features which, in turn determine fundamental material properties. Control of segregation is a major area of industrial research, yet the understanding of the behavior of alloying elements is incomplete. The microgravity environment offers an ideal opportunity to study the basic properties of segregation for purposes of determining the influence of gravity-related phenomena. Such understandings would have significant impact on strategies of process control in the production of, for example, large iron-nickel superalloy ingots.

Nickel-iron meteorites may often be viewed as iron-nickel alloys which solidified in a vacuum under microgravity conditions (1, 2). Their macro/micro-structural features exhibit strikingly regular patterns over a range of compositions and processing conditions - conditions which may never be more precisely determined.

Many meteoritic macro/microstructures have been extensively analyzed by standard, modem material analyses such as microprobe techniques. Descriptions of meteoritic masses, ranging from a few grams to many kilograms, are readily available in the literature of meteoritics. As large microgravity research specimens, nickel-iron meteorites can, therefore, provide insights into fundamental segregation behavior for the following reasons:

- Meteoritic macrostructures exhibit regular, three-dimensional patterns of nickel, carbon, sulfur and phosphorus segregation and compound formation visible to the naked eye. Individual crystals can sometimes be measured in centimeters.

- Meteoritic microstructures contain many compounds that are similar in chemistry and crystal structure to those of important industrial earth alloys.

Most macrostructural features of a metal are often determined during solidification; microstructural features can reflect both solidification and solid state reactions. This paper will discuss the potential for linking microgravity segregation research to the study of complex iron-nickel alloy segregation through the examination of nickel-iron meteorite structures. We briefly describe the compounds formed by the major alloying elements: Ni, S, C, P, Co and Cr. The Handbook of Iron Meteorites (3), a comprehensive guide to nickel-iron meteorites, is used for standard definitions, compositions and descriptions. Each descriptive section is based in classical meteoritics; each discussion section is our reinterpretation of these macro/micro-structural features. This paper gives an indication of the type of information in the meteoritics literature that is of potential interest to Researchers in microgravity science, materials science and, more specifically, the metallurgy of iron-nickel superalloys.

Terminology

The Widmanstätten structure (Figure la) is a characteristic and identifying feature of the largest class of nickel-iron meteorites, the octahedrites. This morphology is formed by body-centered cubic lamellae of delta ferrite (kamacite) growing in the <110> direction, which defines an octahedral plane (Figure lb). The delta ferrite phase is encased by a thin layer of austenite/taenite (This relationship is discussed in more detail below.)_ Octahedrites exhibiting a typical Widmanstatten structure are shown in Figure 2 (a-d).

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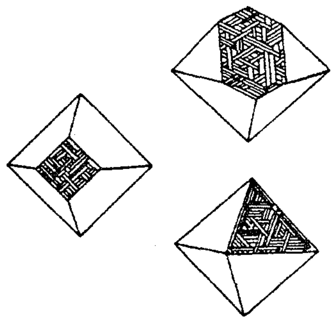

Figure la: Schematic of **Widmanstätten** structure (3).

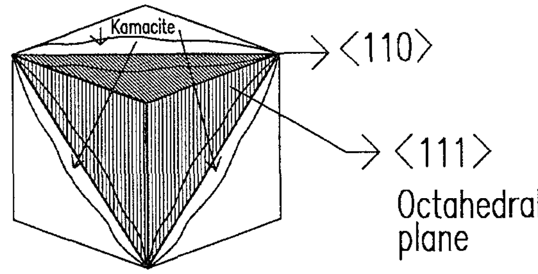

Figure lb: **Widmanstätten kamacite/delta** ferrite growth in the <110> direction defines a <111> octahedral plane.

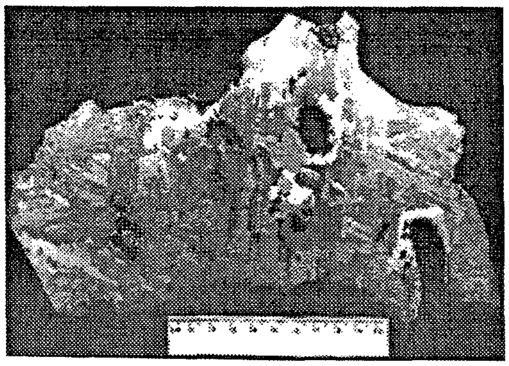

Figure 2a. Youndegin, West Australia, nickel-iron meteorite with FeS-graphite inclusions (black) surrounded by delta ferrite (white). Courtesy of Dr. C. B. Moore.

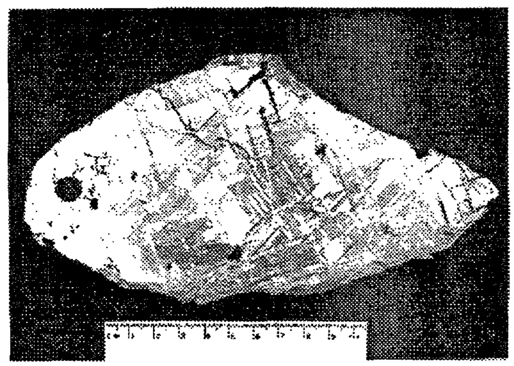

Figure 2b: Kingston, New Mexico, nickel-iron meteorite with large **FeS** nodule. Courtesy of Dr. C. B. Moore.

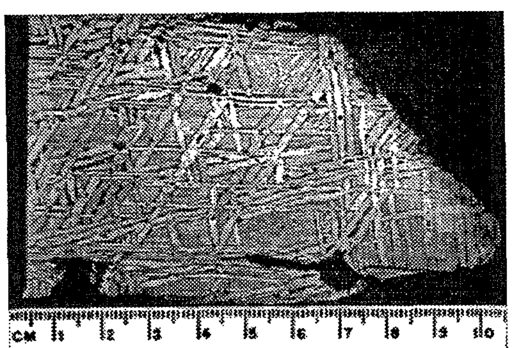

Figure **2c**: Plymouth, Indiana, nickel-iron meteorite. Courtesy of Dr. C. B. Moore.

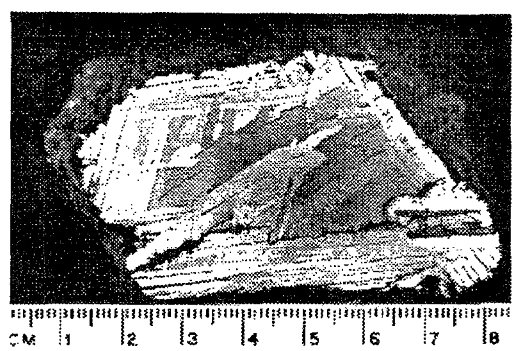

Figure 2d: Leeds, Quebec, Canada nickel-iron meteorite. Courtesy of Dr. C. B. Moore.

Table 1 - Chemical Compositions And Crystal Structures Of Major Nickel-Iron Meteorite Phases

METEORITIC TERMINOLOGY	METALLURGICAL TERMINOLOGY	STRUCTURES AND COMPOSITIONS IN WEIGHT PERCENT
Kamacite	Delta ferrite (1,2)	Body-centered cubic iron Ni: 4 to 7.5% Co: 0.4-0.6% (3)
Taenite	Austenite (3)	Face-centered cubic iron with Ni 25 - 50%; Co .3 - .8% c .05 - .5%; P .05 - .1% (3)
Plessite	No direct equivalent based on composition (3)	Two-phase mixture of kamacite and taenitk, often seen as a "fine scale" Widmanstatten structure (3)

Table 2 Nickel-Iron Meteorite Structural Class, Size of Delta Ferrite Crystal and Corresponding Nickel Content (3)

Structural Class	Delta Ferrite Bandwidth, mm	Ni Content, Weight Percent
Hexahedrites	A smooth single crystal	5.35 - 5.75
Coarsest Octahedrites	>3.3	5.5 - 6.9
Coarse Octahedrites	1.3 - 3.2	6.5 - 8.8
Medium Octahedrites	0.5 - 1.3	9.9 - 11.4
Fine Octahedrites	0.2 - 0.5	11.3 - 13.3

Table 1 gives a brief overview of major metallic meteorite phases and compares meteoritic and equivalent metallurgical terms. Classical meteoritics theory views kamacite as alpha ferrite, the product of a solid state phase transformation; we have reinterpreted kamacite as delta ferrite (1,2).

Description - Nickel

Nickel is the single most important alloying element in determining nickel-iron meteorite macrostructural features. Iron with 4-7.5% nickel in solid solution forms body-centered cubic delta ferrite, the major phase of these materials. Delta ferrite macrostructural morphology varies with nickel content from large single crystals at the low nickel end to the classic octahedral Widmanstatten morphology in the intermediate range, to a multitude of fine-grained crystals at high nickel concentrations.

The structural, descriptive classification of nickel-iron meteorites is based on this variation in nickel content as follows:

- Hexahedrites - Hexahedrites, with Ni content between 5.3-5.7 weight percent, are large single crystals of delta ferrite.
- Octahedrites - Figure 2 (a-d) - Ni content in this class is in the range from roughly 5.5 to approximately 16 weight percent. The octahedrite class is subdivided according to the size of the delta ferrite crystals which, in turn is inversely related to bulk nickel content. This relationship is shown in Table 2.
- Ataxites - When bulk nickel content reaches the 16-20+ weight percent range, the delta ferrite crystals become very small and require a hand lens for identification.

A typical delta ferrite lamella is a finger to plate-shaped crystal with the length, height and width ratio: 30:3: 1 (3). Width ranges between <0.2 and 3.3 mm; length can be up to several centimeters. Delta ferrite morphology and nickel content is the basis for the further refinement in the structural classification of nickel-iron meteorites shown in Table 2.

Austenite, classically described in meteoritics as a single phase, face-centered cubic solid solution of 25-50% nickel in iron, is found in nickel-iron meteorites of all classes. In the meteoritic Widmanstatten structure, austenite encases delta ferrite lamellae in a thin layer with the epitaxial relationship:

<111> austenite/<110> delta ferrite.

Microprobe analyses show that meteoritic austenite is actually a complex, heterogeneous region composed of an austenite matrix of varying nickel content which contains several secondary phases (4).

Plessite is described as a two-phase mixture of delta ferrite and austenite without a direct earth-alloy equivalent (3). Metallograpbically, it generally appears as a fine scale Widmanstatten structure between the larger Widmanstatten delta ferrite lamellae. Plessite also exhibits a variety of morphologies described as pearlitic, spheroidiied, acicular, comb, net, cellular, finger, and duplex. This microstructure is described in more detail below.

Discussion - Macrostructural Features

Classical meteoritics theory views the Widmanstatten structure as a solid state phase transformation produced in the 600-400C range at a cooling rate of 1 to 10 degrees every million years (5). The formation of delta ferrite-austenite mixtures can also be described in terms of the microgravity solidification concept.

The macro-scale, three dimensional octahedral morphology of the meteoritic Widmanstätten structure seen in Figure 2(a-d) have not been reproduced on earth and may be unique to the microgravity environment. It can be interpreted as delta ferrite solidification cells surrounded by austenite formed in a peritectic transformation in the low nickel, high temperature region of the iron-nickel phase diagram (See Figure 3).

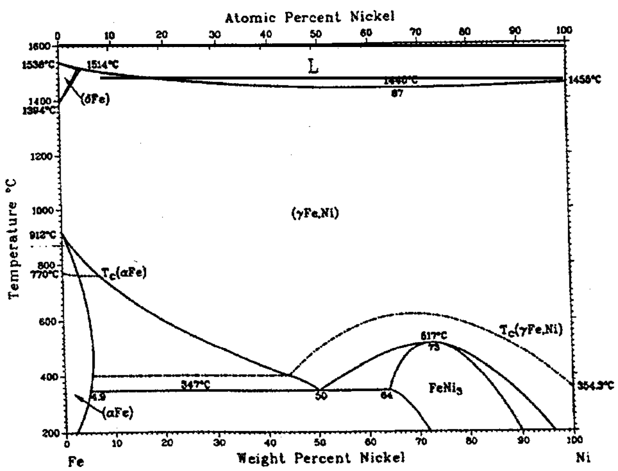

Figure 3 - Fe-Ni phase diagram (6).

There are two forms of ferrite found on the equilibrium Fe-Ni phase diagram at low nickel compositions - alpha ferrite and delta ferrite. Alpha and delta are crystallographically identical body-centered cubic phases. Given proper chemistries and cooling conditions, either one can be preserved in a microstructure at room temperature (7). Delta ferrite is commonly retained in ferritic and austenitic stainless steels (8). The other solid phase of interest in this region, gamma austenite, is a face-centered cubic crystal structure.

The delta ferrite phase can be formed directly from the liquid in a solidification reaction at temperatures between about 1538C and 1394C. At low nickel-concentrations and, again equilibrium conditions, gamma austenite is formed in the high temperature peritectic reaction directly from the liquid. A peritectic transformation is

Solid1 + Liquid ---> Solid2

or, in terms of this phase diagram, on cooling, between 1538C and 1394C:

Delta ferrite + Liquid ---> Gamma austenite.

At higher nickel concentrations, on equilibrium cooling, gamma austenite can be formed directly from the liquid. Alpha ferrite can be formed from gamma austenite on cooling in a solid state reaction below 912C.

Metallurgical phase diagrams are equilibrium phase diagrams. All phase changes are assumed to be equilibrium reactions. Most materials, whether natural like the meteorites, or industrial alloys, do not involve simple binary alloys. Research on steels, for example, has demonstrated that some alloying elements widen phase boundaries, while others make them more narrow. Composition on a "local" scale can have significant effect on the phases produced. As cooling rates increase, equilibrium phase transformations are suppressed and metastable phases may be formed at higher temperatures and preserved in the final, room temperature microstructure. Diffusion kinetics associated with the cooling of a non-homogeneous system are complex.

Epitaxial nucleation, in which a forming phase has a preferred crystallographic relationship with a pre-existing phase, can produce the <111> austenite/<110> delta ferrite relationship. With the delta ferrite as the first solid formed, the phase formed in the peritectic reaction (or directly from the melt), has a substrate on which to form. The rate of the peritectic transformation is dependent on diision through the liquid above the peritectic temperature. The cubic symmetry of both delta ferrite and alpha ferrite (BCC) coupled with that of austenite (FCC) has also contributed to confusion. The same <110> ferrite/<111> austenite relationship can be produced by the two very different formation conditions under discussion: solidification from a melt plus a peritectic transformation or nucleation and growth in the solid state.

The same microstructure can be formed by both scenarios. Only the order of phase transformation events is reversed between them. At room temperature, alpha kamacite and delta kamacite are both body-centered cubic nickel-iron. A prior knowledge of their thermal histories (7) or a detailed study of their chemical gradients (9) is required to distinguish between them. A discussion of a model for meteorite thermal history is given later.

Plessite, the last nickel-rich area to solidify, represents the terminal transient, a two-phase region, trapped between the large delta ferrite lamellae.

Listed below are features of the Widmanstätten structure that have the potential for providing additional insights into fundamental material properties.

- The inverse relationship between nickel content and delta ferrite lamella bandwidth in Table 2 may be a gravity independent characteristic of this alloy system within this relatively narrow nickel range.
- In contrast with <110> kamacite/delta ferrite growth direction, ferrous earth alloys grow in the <100>, cubic direction. The octahedral morphology can be interpreted as a strategy for minimizing total system energy during solidification, a surface area to volume relationship intermediate between the sphere and the cube.
- Individual delta ferrite lamellae can reach several centimeters long and the overall octahedral morphology can be preserved in the macrostructure on a scale not possible in earth alloys. For example, the entire 20 ton, 6.6 foot diameter Cape York (Agpalilik) nickel-iron meteorite is a single crystal (3). These macrostructures, when viewed as microgravity solidification specimens, present a unique opportunity for the study of crystal growth and segregation phenomena.

Figure 4: Typical meteoritic delta ferrite-austenite-plessite region. Region A is delta ferrite/kamacite; B is austenite/taenite; C-D-E is classically described as plessite.

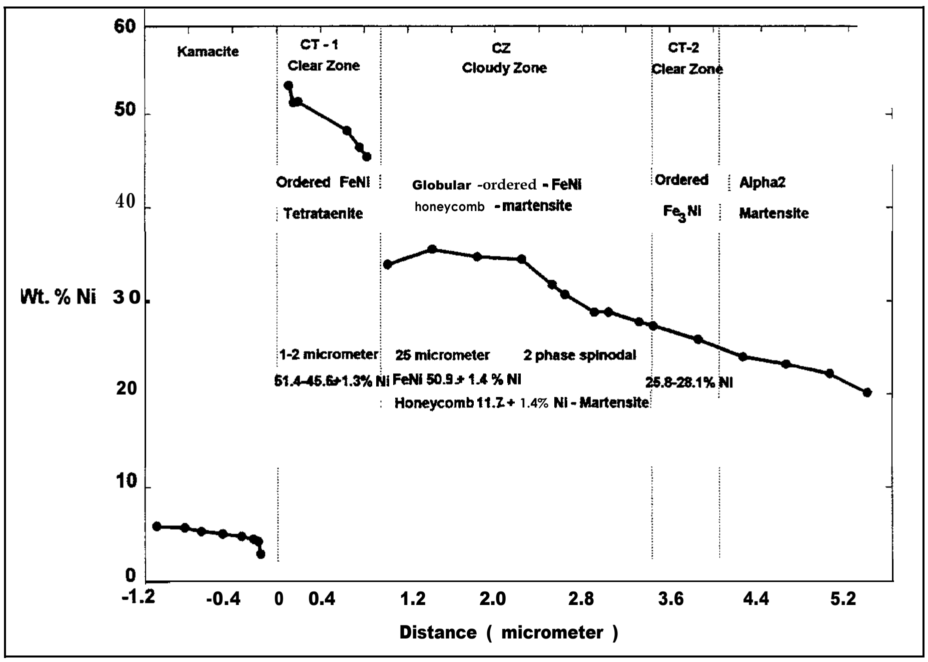

Figure 5: Schematic microprobe trace of typical nickel-iron meteorite phase regions. After reference (4).

Discussion - Microstructural Features

Microstructural features of a typical delta ferrite-austenite region at a magnification of 500x are shown in Figure 4. The light region A, is delta ferrite, with the lowest Ni content; region B, classically described as taenite, is nickel-rich, Ni-content decreases across plessite region C-D-E (microprobe data unpublished). The acicular structures in C and D may be martensites of slightly diierent composition. The block-like nickel-iron compound in E is a region with the lowest average nickel content. This figure shows that plessite is more complex than its classic definition as a mixture of kamacite and taenite.

Goldstein and his colleagues (4) have performed extensive microprobe work on this delta ferrite-austenite region. A schematic of a microprobe analysis across a typical meteoritic delta ferrite/austenite region is shown in Figure 5. Here, we interpret their results in the light of microgravity solidification and suggest that these analyses present an opportunity for insights into the solidification of complex earth alloys such as the iron-nickel superalloys.

Another way to describe the sub-regions within the austenite is in terms of their relative nickel (or solute) content. For example, the CT-l region of Figure 5 is solute-rich, while the CT-2 region is relatively solute-lean. This same terminology is used by metallurgists to describe a class of defects in iron-nickel superalloy ingots: freckles (solute rich) and white spots (solute lean).

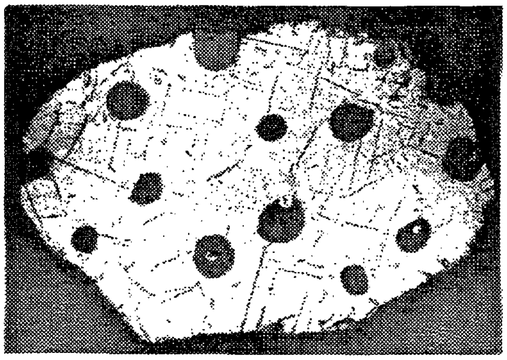

Figure 6a: Bear Creek, Co, nickel-iron meteorite showing FeS nodules. Oriented thin, grey lines are phosphides. Courtesy of Dr. C. B. Moore.

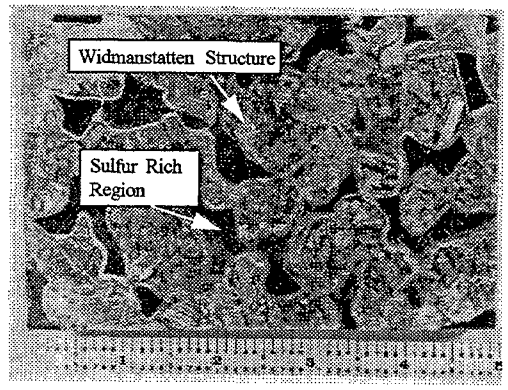

Figure 6b: Mundrabilla nickel-iron meteorite with 8% bulk sulfur. Widmanstatten structure is surrounded by high sulfur/iron phase.

The iron-nickel superalloy ingots are melted in vacuum or under a slag cover to prevent oxidation (10). The segregation defects in these ingots are attributed to gravity driven fluid flow related events. The solute rich regions (freckles) are a result of the upward flow of lighter solute rich inter-dendritic fluid. Diierent mechanisms are attributed to the formation of the solute lean (white spots) defects. A common mechanism is the fall-in of as cast dendrites from the electrode or the solidifying edge (shelf) into the melt pool. This material would quickly fall to the bottom of the pool and be trapped in the mushy region resulting in a solute lean region in the solidified ingot. Gravity plays an important role in all the mechanisms described above. These mechanisms have not been found adequate to describe all the segregation defects found in these ingots.

Some of the phases and phase relationships in Figures 4 and 5 as well as others discussed in this paper are common across a large population of meteorites containing iron and nickel. Some of these same phases and phase relationships are also common to earth alloys. The commonalities probably represent fundamental, gravity independent phenomena. For example, we suggest that a comparative study of meteorites and iron-nickel superalloys may provide insights into defect mechanisms in this alloy class. Common segregation behavior could be associated with fundamental material characteristics. Strategies to control such behavior would then be different from strategies to control gravity-related segregation behavior.

Description - Sulfur

Sulfur content in the 0.2-1% range is common in nickel-iron meteorites; in a few cases, bulk sulfur can reach 8% to 12% (3). Meteoritic iron sulfide occurs in the stoichiometric compound, FeS, called troilite. On earth, iron and sulfur form pyrite, FeS2, and pyrrhotite, $Fe_{1-x}S$.

FeS is often seen as spherical nodules completely surrounded by the Widmanstätten structure (Figure 6a). These nodules also contain graphite and phosphides. FeS also occurs as shapeless nodules, bars and dumbbells. Smaller nodules can be bar-, diamond- or plate-shaped. Nodules in a few meteorites show a parallel orientation of large FeS nodules aligned with the local Widmanstiitten structure.

Discussion

Although ubiquitous in iron ores, the sulfur content of industrial ferrous alloys is usually restricted to a few hundredths of a percent by specification. This is because sulfur in very small amounts can form low-melting temperature compounds which can significantly weaken a ferrous material.

From a general knowledge of the Fe-Ni and Fe-S equilibrium phase diagrams and a familiarity with meteoritic microstructures, it is evident that FeS freezes later than delta ferrite. The patterns of FeS segregation in nickel-iron meteorites therefore offer a unique opportunity to study sulfur segregation behavior. For example, the alignment of the FeS nodules with the local Widmanstatten structure in certain meteorites described above remains unexplained.

Mundrabilla, Figure 6b, with a reported bulk sulfur content of 8%, is considered atypical (3). A sulfur print (not shown) reveals that Mundrabilla's Widmanstatten structure is encased in FeS, rather than the more typical case in which the reverse is true (Fig. 2a-b). Mundrabilla's macrostructure resembles two immiscible liquids, one rich in iron-nickel, the other sulfur-rich, that solidified under relatively quiescent conditions. Mundrabilla's macrostructure illustrates that, as the sulfur content increases significantly, the volume fraction of the sulfur-rich phase increases enough to change the convex/concave - i.e., surface tension - relationship between Widmanstiitten regions and the FeS.

Description - Carbon

Carbon content in nickel-iron meteorites ranges from 0.005% to 2%. Buchwald (3) describes carbon as "inhomogeneously distributed" across the general meteorite population and states that it is diicult to arrive at true bulk analytical data. A population of chemically and structurally related nickel-iron meteorites, considered carbon-rich, contains 0.2-2% carbon. Table 3 summarizes the three major meteoritic carbon compounds.

Discussion

Meteoritic carbon compounds hold potential for revealing fundamental insights into gravity independent segregation behavior because:

Table 3 Major Nickel-Iron Meteorite Carbon Compounds (3)

Compound and Crystal Structure	Description
Graphite Hexagonal	• Centimeter-sized nodules with FeS and silicates • Lamellae and spherulites
Cohenite Orthorhombic	• (Fe, Ni, $Co)_3C$; Similar to Fe_3C cementite • Ni 0.7 - 2.3 %; Co 0.02 - 0.3% • Decomposes to ferrite + graphite
Haxonite Cubic	. $(Fe,Ni,Co)_{23}C_6$; Similar to $M_{23}C_6$ carbide . Ni 3.5 - 5.6 %; Co 0.05 - 0.4% • Decomposes to ferrite + graphite

- There is a close relationship between carbon compounds in nickel-iron meteorites and steels shown as seen in Table 3.

- They are found in both the thermodynamically stable hexagonal form and the unstable orthorhombic and cubic forms within the general population of nickel-iron meteorites.

Description - Phosphorus (3)

Bulk phosphorus content in iron meteorites ranges between 0.01-2%. Phosphorus forms a compound of the general formula $(Fe,Ni)_3P$, called schreibersite, a tetragonal crystal structure which forms a variety of morphologies and can often be readily identified in photomicrographs. (See Figure 6a.)

Description - Cobalt and Chromium (3)

Co and Cr are present in relatively minor, but metallurgically significant amounts in the nickel-iron meteorites. Because Co and Cr are important alloying elements in earth alloys, their segregation tendencies and microstructural morphologies hold information of potential significance for a complete understanding of gravity independent segregation.

Bulk Co content ranges between 0.32 and 1.0 weight percent; average values are in the 0.4-0.6 weight percent range. Co is found in phases which contain Fe and Ni: delta ferrite, austenite, carbon and phosphorus phases.

When present, Cr can be found in solid solution with delta ferrite and austenite. Cr also forms the compounds FeCr204, Fe Cr_2S_4 and CrN.

Thermal History

Only the broad outlines of nickel-iron meteorite thermal history as microgravity castings can be deduced. Since liquids have no memory, this outline begins at the melting/freezing point of pure iron. A typical nickel-iron meteorite is modeled as a multi-kilogram ferrous liquid sphere solidifying under microgravity conditions in outer space (Figure 7). The mass in this calculation has a range of approximately 23 kg as a lower boundary (meteorite); the upper boundary is a mass 10 km in diameter (asteroid). It is assumed that the structures observed within these meteorites is produced by cooling from the molten state.

To obtain estimates of the effective formation times of these structures, the meteorite has been modeled as a molten sphere at the melting point of pure iron. Observed structures can only form after solidification has begun.

The boundary conditions are that meteor cooling occurs by radiation and obeys the fourth power Stephan - Boltzmann radiation law. An estimate of the emissivity of the surface is 0.37. The temperature dependence of the emissivity is not considered in this approximate calculation. The latent heat of solidification is treated as an excess temperature added to the melting point of the meteoritic material. The cooling time is calculated as the time required for the center of the meteorite to reach the freezing point of iron. For an iron mass with a diameter of 1.8 meters, the solidification time is 1.6 hours; for a 10 kilometer diameter iron body, solidification occurs after 3400 years.

Since the meteor in space is not subjected to disturbing forces, the solidification front will have a spherical shape and move radially inward as radiational cooling proceeds. Solidification structures are formed at the solid/liquid boundary and will continue to follow this boundary until the center has solidified.

Nickel-Iron Meteorites as Research Specimens - Gibeon and Mundrabilla

Gibeon nickel-iron meteorite, characterized as comparable to iron-nickel pressure vessel steel in composition (3), illustrates the type of information in the literature of meteoritics which may be of interest to other scientific disciplines. Gibeon has been studied extensively since the first specimens were reported in 1838. A summary of information extracted from (3) of pertinence to Gibeon's potential as a microgravity research specimen is given in Table 4.

In describing Gibeon, Buchwald states, “In the individual grains, more lamella directions than can be accounted for by the Widmanstätten law are developed” (3). This phenomenon is of interest because it raises the possibility of potential insights into the control of grain orientation, considered a defect in some industrial alloy applications.

In contrast with Gibeon's characterization as a typical member of the fine octahedrite group, Mundrabilla (Figure 6b) is a structurally “anomalous” medium octahedrite. A description of Mundrabilla is given in Table 5 (Also see the discussion in Sulfur section.).

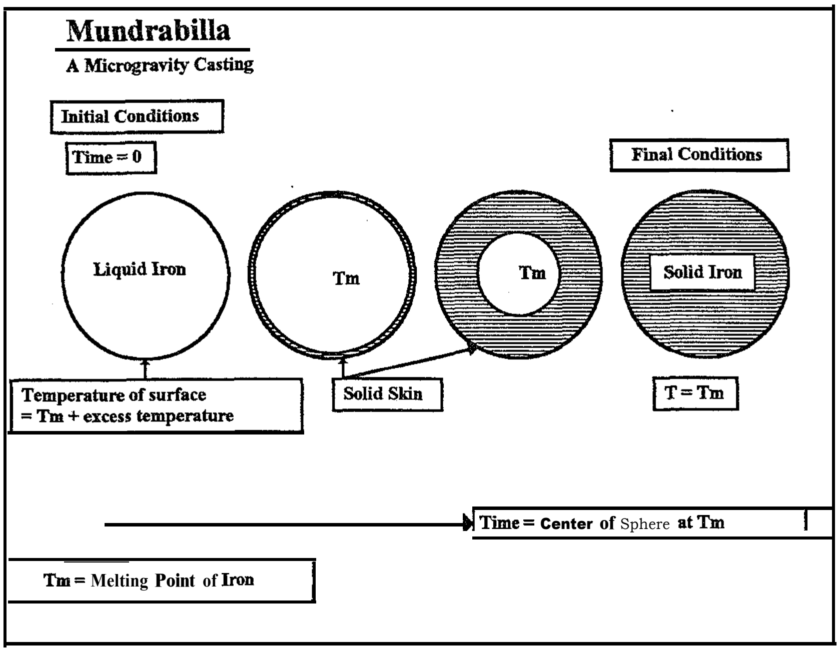

Figure 7: A typical nickel-iron meteorite modeled as a multi-kilogram ferrous liquid sphere solidifying under microgravity conditions in outer space.

Table 4 Gibeon Nickel-Iron Meteorite (3)

Mass (recovered and reported): • 75 masses with an average weight of 280 kg • Individual specimens range from 195g to 650 kg
Composition: • 7.93% Ni, 0.41% Co, 0.04% P Troilite/FeS: • Ubiquitous as nodules 0.5 to 25 mm in diameter and elongated lenses typically 10 x 1 mm • Elongated troilite bodies (0.5-2 mm wide) have segregated in the grain boundaries • Near-surface nodules show a corroded iron phase but are otherwise well-preserved • Very low P content and few inclusions
Widmanstätten structure - homogeneous : • Fine octahedrite • Crystallographically-related Widmanstätten regions range from 10 to 50 cm • Kamacite lamellae: Length to width ratio of 40: 1; Width of 0.30 +/-0.05 mm
Chromite ($FeCr_2O_4$) occurs sparsely as 0. l-l mm euhedric crystals, usually associated with FeS.
Cohenite and phosphides are absent.
Mechanical properties: • Very ductile - sustained a 180° bend test without fracturing • Tensile strength - 41.4 kg/mm^2

Table 5 Mundrabilla Nickel-Iron Meteorite (3)

Mass (recovered and reported): 2 pieces: 6.1 t and 16 t plus numerous smaller masses
Composition: • 7.8% Ni, 0.26% P, 1%C, about 8% S • Very high S content - second highest S content of any known nickel-iron meteorite (highest is 12%)
Widmanstätten structure: . Medium octahedrite with anomalous Widmanstiitten structure • Kamacite lamellae: Length to width ratio of 20: 1; Width of 0.55 +/-0.10 mm
FeS and Graphite - abundant

Mundrabilla is of interest in the light of the present discussion because:

- In a typical nickel-iron meteorite, the Widmanstätten structure encases troilite nodules. In Mundrabilla, the troilite encases the Widmansttitten structure. This can be interpreted as a change in the surface tension relationship between two immiscible liquids due to a significant increase in the volume fraction of the S-rich phase.

- Mundrabilla's graphite, located within the kamacite, is characterized as "fan shaped." While meteorites contain many graphite morphologies in common with earth alloys, Mundrabilla's fan graphite is unique to meteorites and limited to only a few other meteorites. The reason for this unusual graphite morphology is unclear, but may be the result of Mundrabilla's high sulfur concentration. In iron-nickel superalloys, bulk sulfur is kept below 0.03 percent by specification.

Thus, Gibeon and Mundrabilla contain information of potential interest to microgravity researchers and industrial metallurgists.

Conclusion

Nickel-iron meteorites contain phases and macro/microstructural features that are almost, but not quite, familiar to today's industrial metallurgist. The information contained within the meteorites can be classified as follows:

- Microgravity features-The three-dimensional growth of large, crystallographically related areas seen in the Widmanstiitten structure can probably be attributed to formation in a microgravity environment. As products of microgravity solidification, nickel-iron meteorites provide an opportunity to gain insights into the following:

  - Co-existence of phases of different densities.
  - Growth in crystallographic directions not observed on earth.
  - Uninhibited, three dimensional growth.
  - Large single crystals.

  Observations on microgravity-grown crystals could yield data on fundamental crystal-forming processes by reducing the distortion of gravitational effects.

- Gravitv indenendent features - The close similarity between phases in nickel-iron meteorites and earth alloys are probably gravity independant - i.e., related to the strong, fundamental crystallization forces. Familiar features include the close relationship between delta ferrite, austenite, sulfides, carbides, graphite, and martensite. Strategies to control industrial processing of these features should not focus on gravity induced effects.

- Interaction between microeravitv and gravity independent features - Phase compositions, phase relationships and crystal morphologies unique to meteorites may be attributable to one of the following:
  - Chemical compositions at concentration levels not found naturally on earth or in industrial alloys.
  - "Container-less processing" in space.

Using the vast data available fiom the meteoritics literature, microgravity experiments could be designed to more clearly distinguish among gravity independent, microgravity and earth gravity related phenomena. Information gained could then be applied to the control of earth based processing as well as the design of new materials.

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