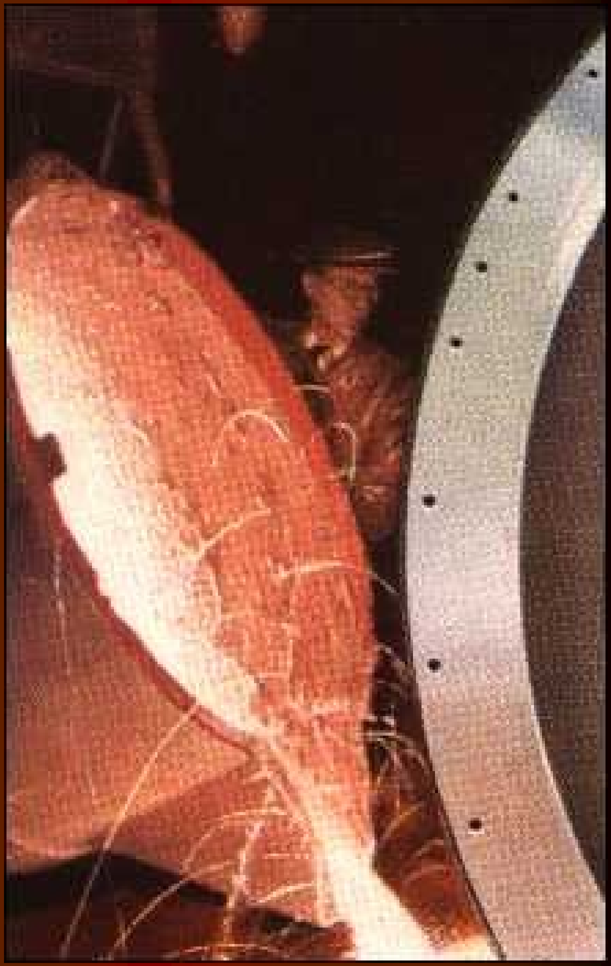
Metallurgical Properties of Cast Irons

~The worlds best element~

Cast Irons

- Cast iron is made when pig iron is re-melted in small cupola furnaces (similar to the blast furnace in design and operation) and poured into molds to make castings. Cast Iron is generally defined as an alloy of Iron with greater than 2% Carbon, and usually with more than 0.1% Silicon.
- Exception: Silicon and other alloying elements may considerably change the maximum solubility of Carbon in Austenite. Thus certain alloys can solidify with a eutectic structure having less than 2% Carbon.



A Brief History of Cast Irons

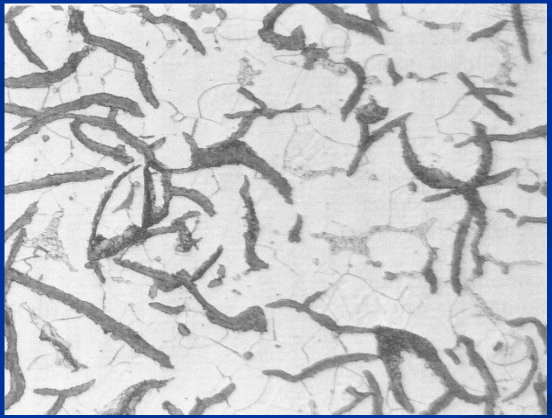
- Cast iron has its earliest origins in China between 700 and 800 B.C.
- Until this period ancient furnaces could not reach sufficiently high temperatures.
- The use of this newly discovered form of iron varied from simple tools to a complex chain suspension bridge erected approximately 56 A.D.
- Cast iron was not produced in mass quantity until fourteenth centaury A.D.

Classifications of Cast Iron

- White Iron: large amount of carbide phases in the form of flakes, surrounded by a matrix of either Pearlite or Martensite. The result of metastable solidification. Has a white crystalline fracture surface because fracture occurs along the iron carbide plates. Considerable strength, insignificant ductility.

- Gray Iron: Graphite flakes surrounded by a matrix of either Pearlite or $\alpha-$Ferrite. Exhibits gray fracture surface due to fracture occurring along Graphite plates. The product of a stable solidification. Considerable strength, insignificant ductility.

Microstructure of White Cast Iron

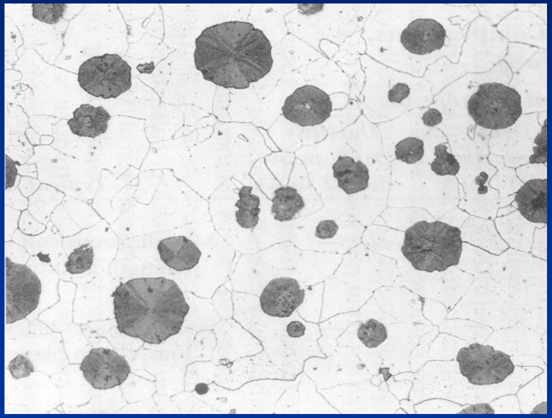


Microstructure of Gray Cast Iron

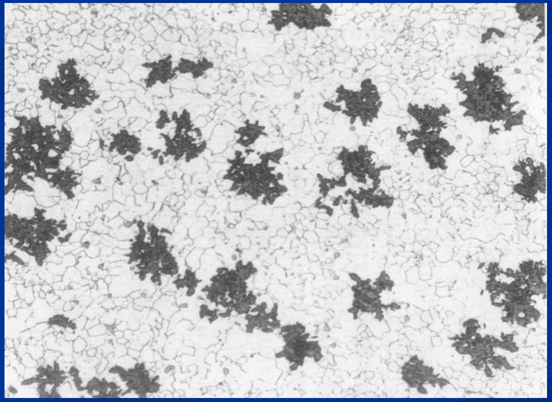
Classifications of Cast Iron

- Ductile (Nodular) Iron: Graphite nodules surrounded by a matrix of either α–Ferrite, Bainite, or Austenite. Exhibits substantial ductility in its as cast form.

- Malleable Iron: cast as White Iron, then malleabilized, or heat treated, to impart ductility. Consists of tempered Graphite in an α–Ferrite or Pearlite matrix.



Microstructure of Ductile Iron



Microstructure of Malleable Iron

Solidification of phases in Cast Irons, Nucleation & Growth of Graphite

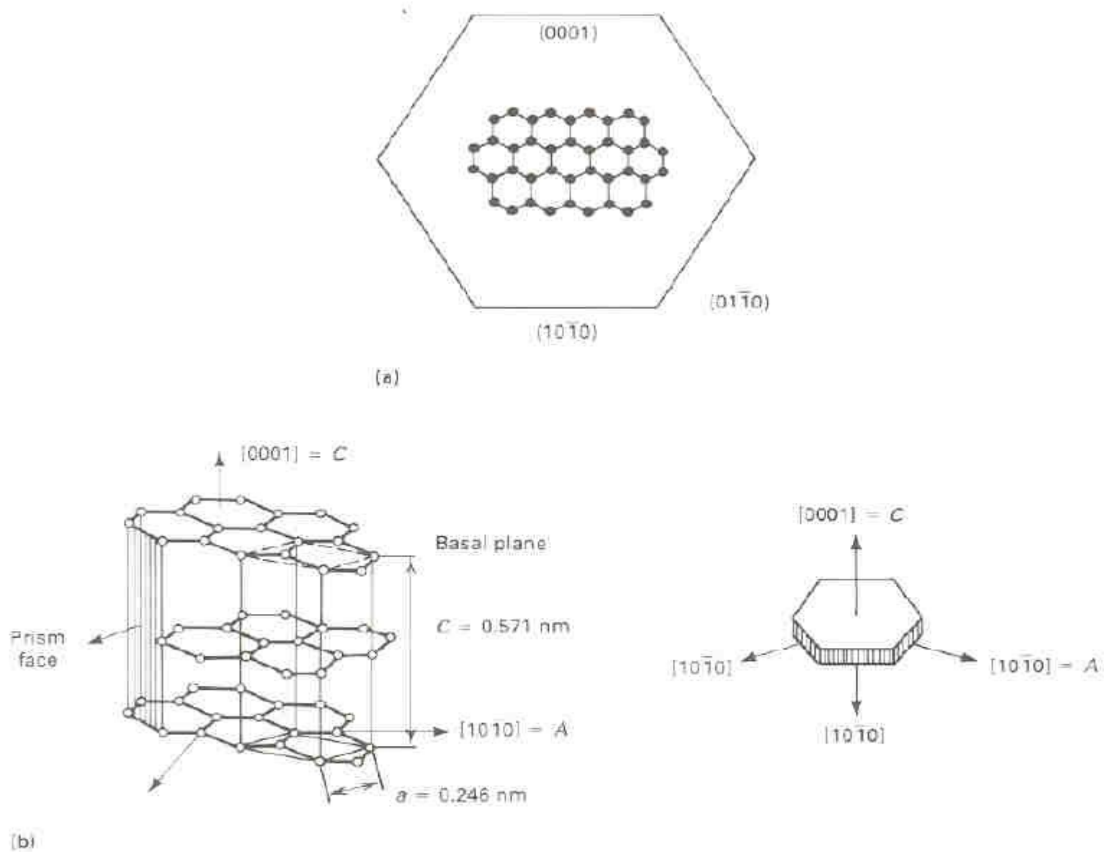


Fig. 3 Crystalline structure of graphite. A and C, possible growth directions. (a) Crystal of graphite bounded by (0001) and (10$\bar{1}$0) type planes; the hexagonal arrangement of the atoms within the (0001) plane is shown relative to the bounding (10$\bar{1}$0) faces. (b) Hexagonal structure of graphite showing the unit cell (heavy lines). Source: Ref 5

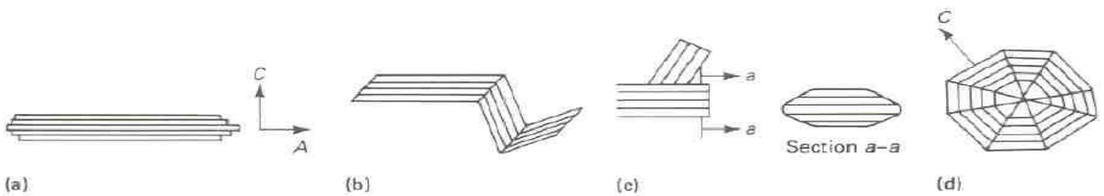


Fig. 4 Schematic of graphite types occurring in the austenite-graphite eutectic. (a) Flake graphite. (b) Compacted/vermicular graphite. (c) Coral graphite. (d) Spheroidal graphite

- Graphite structure is a factored crystal bounded by low index planes.
- Growth occurs along (10$\bar{1}$0) & (0001) planes (direction A & C). Unstable growth occurs along direction A, giving the Graphite microstructure rough, poorly defined, edges in certain areas.
- When grown from the solidification of liquid Iron Carbon alloys, Graphite takes on a layer structure. Among each layer covalent chemical bonds with strengths between (4.19E5 - 5E5)J/mol exist. Between layers weaker bonds exist on the order of (4.19E3 - 8.37E3)J/mol.
- The structure of the Graphite depends on the chemical composition, the ratio of temperature gradient to growth rate, and the cooling rate. Such structures are:
- Flake or Plate Graphite (a)
- Compacted vermicular Graphite (b)
- Coral Graphite (c)
- Spheroidal Graphite (d)

Nucleation of Flake and Spheroidal Graphite

- A wide variety of compo-unds and certain metals have been claimed to serve as either inoculants or nuclei for Flake Graphite growth. (Silicon dioxide, silicates, sulfides, boron nitride, carbides, sodium, potassium, calcium, ect...)
- Two methods of growth.
- The nucleation of Flake Graphite Iron occurs mainly on silicon dioxide particles.
- Salt like carbides containing the ion Carbon are used as inoculants. Such carbides include NaHC2 & KHC2 from Group I, CaC2, SrC2, BaC2 from group II, and YC2 & LaC2 from group III.

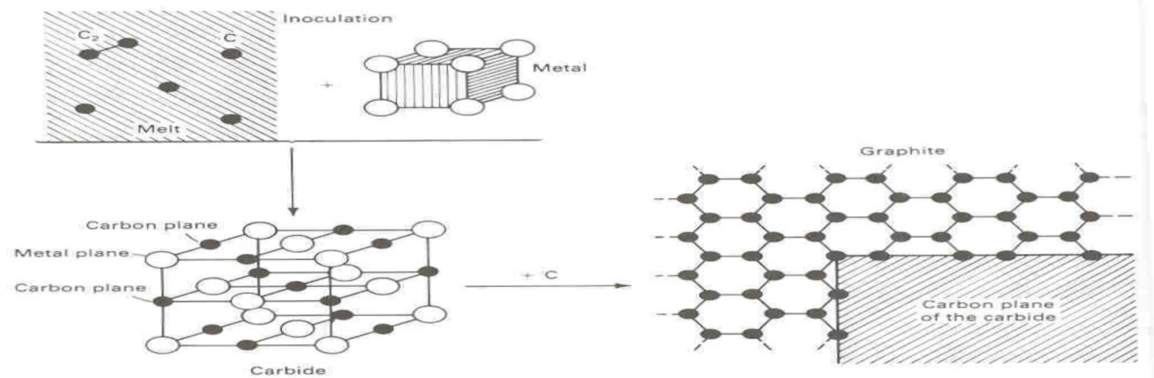


Fig. 8 Schematic of the inoculation of cast iron by metals to form saltlike carbides. Source: Ref 10

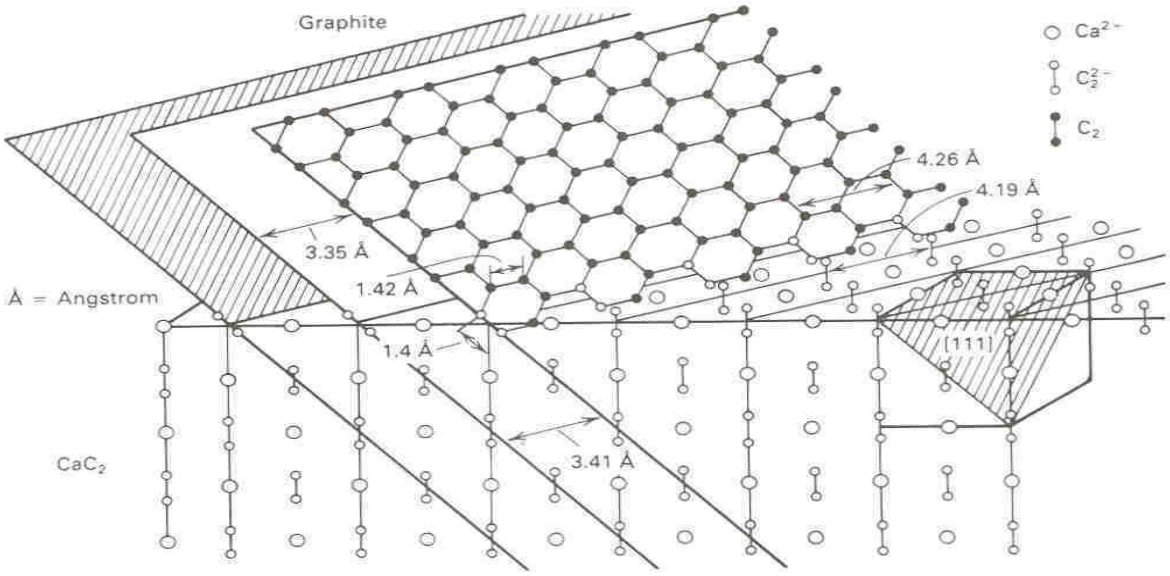
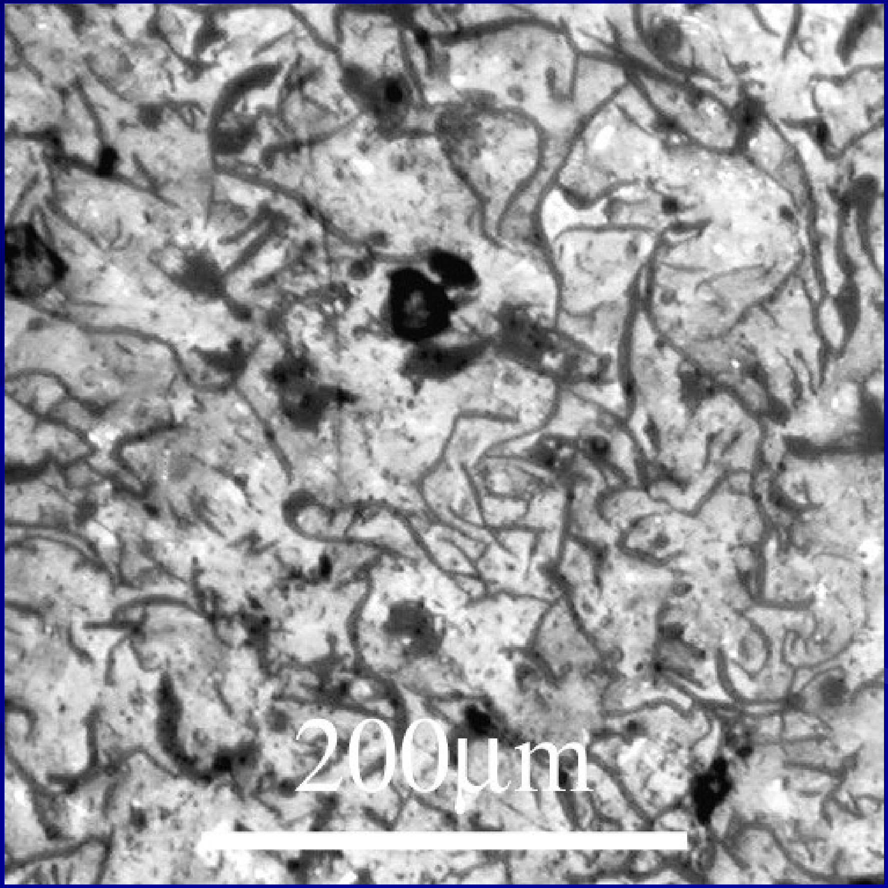


Fig. 7 Epitaxial growth of graphite on a CaC_2 crystal. Source: Ref 10

General Characteristics of White Cast Irons

- White Cast Irons contain Chromium to prevent formation of Graphite upon solidification and to ensure stability of the carbide phase. Usually, Nickel, Molybdenum, and/or Copper are alloyed to prevent to the formation of Pearlite when a matrix of Martensite is desired.
- Fall into three major groups:
- Nickel Chromium White Irons: containing 3-5%Ni, 1-4%Cr. Identified by the name Ni-Hard 1-4
- The chromium-molybdenum irons (high chromium irons): 11-23%Cr, 3%Mo, and sometimes additionally alloyed w/ Ni or Cu.
- 25-28%Cr White Irons: contain other alloying additions of Molybdenum and/or Nickel up to 1.5%



General Characteristics of Gray Cast Irons

- Gray Cast Irons contain silicon, in addition to carbon, as a primary alloy. Amounts of manganese are also added to yield the desired microstructure. Generally the graphite exists in the form of flakes, which are surrounded by an a-ferrite or Pearlite matrix. Most Gray Irons are hypoeutectic, meaning they have carbon equivalence (C.E.) of less than 4.3.

- Gray cast irons are comparatively weak and brittle in tension due to its microstructure; the graphite flakes have tips which serve as points of stress concentration. Strength and ductility are much higher under compression loads.

General Characteristics of Ductile Irons

- As a liquid, Ductile Iron has a high fluidity, excellent castability, but high surface tension. Thus, sands and molding equipment must provide molds of high density and good heat transfer.
- Solidification of Ductile Cast Iron usually occurs with no appreciable shrinkage or expansion due to the expansion of the graphite nodules counteracting the shrinkage of the Iron matrix. Thus, risers (reservoirs in mold that feed molten metal into the cavity to compensate for a decrease in volume) are rarely used.
- Require less compensation for shrinkage. (Designers compensate for shrinkage by casting molds that are larger than necessary.)
- Most Ductile Irons used as cast. Heat treating (except for austempering) decreases fatigue properties. Example: Holding at the subcritical temperature (705˚C) for ≈ 4 hours improves fatigue resistance. While heating above 790˚C followed by either an air or oil quench, or ferritizing by heating to 900˚C and slow cooling reduces fatigue strength and fatigue resistance in most warm environments.
- Austempered Ductile Iron has been considered for most applications in recent years due to its combination of desirable properties. A matrix of Bainitic Ferrite and stabilized Austenite with Graphite nodules embedded. Applications include: Gears, wear resistant parts, High-fatigue strength applications, High-impact strength applications, automotive crankshafts, Chain sprockets, Refrigeration compressor crankshafts, Universal joints, Chain links, and Dolly wheels.

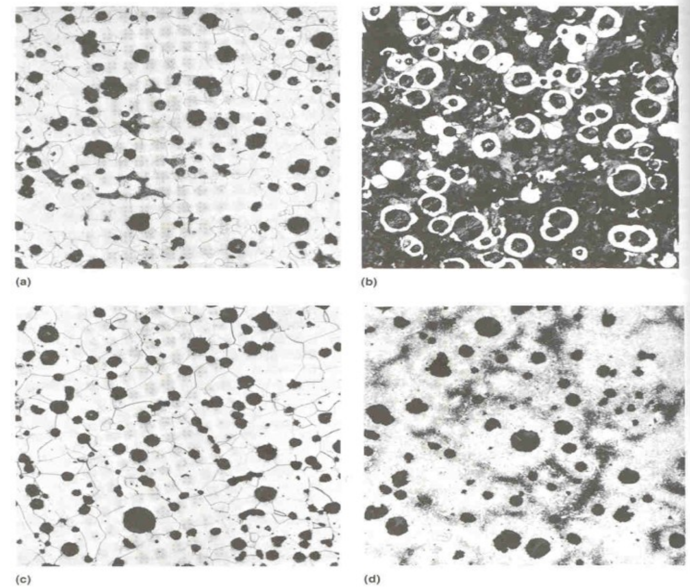


Fig. 1 Microstructures of ductile iron. (a) As-cast ferritic. (b) As-cast pearlitic, hardness 255 HB. (c) Ferritic, annealed 3 h at 700 °C (1290 °F). (d) Pearlitic ductile iron, oil-quenched and tempered to 255 HB. All etched in 2% nital. 100×

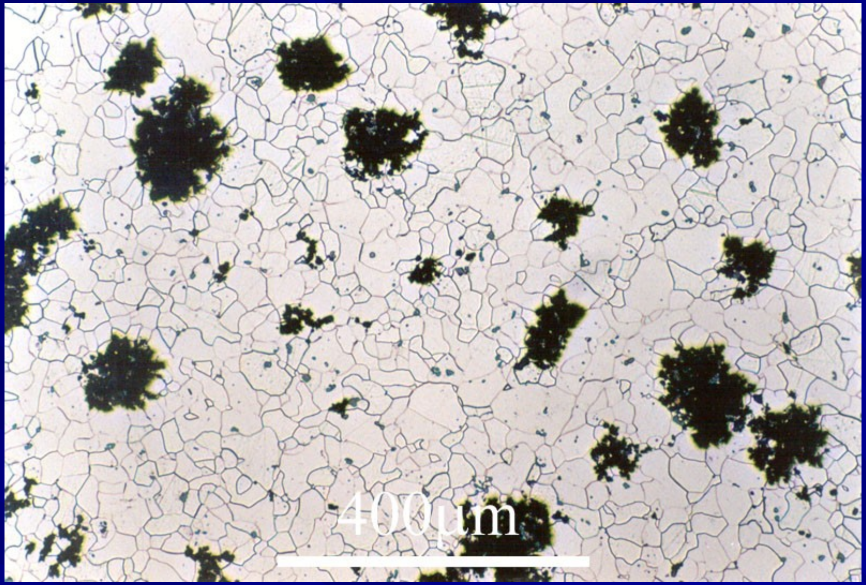
Fig. 2 Austempered ductile iron structure consisting of spheroidal graphite in a matrix of bainitic ferritic plates (dark) and interplate austenitic (white). The heat treat cycle was austenitized at 870 °C (1600 °F) for 3 h followed by austempering at 385 °C (725 °F) for 2 h. 500×. Courtesy of B.V. Kovacs, Kosmar Enterprises

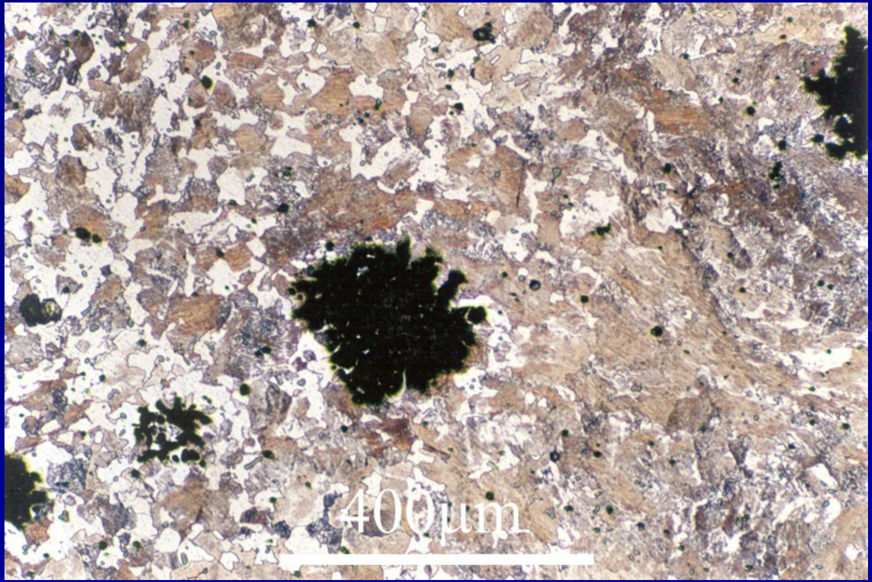
Ductile Iron Applications

- Used for a variety of applications, specifically those requiring strength and toughness along with good machinability and low cost. Casting, rather than mechanical fabrication (such as welding), allows the user to optimize the properties of the material, combine several castings into a desired configuration, and realize the economic advantages inherent in casting.
- Microstructure is consistent; machinability is low due to casting forming the desired shape; porosity is predictable and remains in the thermal center.
- Ductile Iron can be austempered to high tensile strength, fatigue strength, toughness, and wear resistance. Lower density
- Ductile Iron seems to work in applications where theories suggest it should not.
- Ductile Iron shipments exceeded 4 million in 95.
- Cast Iron pipe make up to 44% of those shipments.
- 29% used for automobiles and light trucks (economic advantages and high reliability)
- Other important applications are: Papermaking machinery; Farm equipment; Construction machinery and equipment; Power transmission components (gears); Oilfield equipment.

Malleable Irons

- Type of Iron with Graphite in the form of irregularly shaped nodules.
- Produced by first casting the Iron as a White Iron, then heat treating to transform the Carbide into Graphite.
- Categorized into 3 categories: Ferritic, Pearlitic, and Martensitic Malleable Cast Iron.
- Two types of Ferritic: Blackheart (top) and Whiteheart (not produced in US)
- Posses' considerable ductility and toughness due to the combination of nodular graphite and low carbon matrix. Often a choice between Malleable and Ductile Iron for some applications, decided by economic constraints.
- Solidification of white Iron throughout a section is essential in producing Malleable Iron, thus, applications of large cross section are usually Ductile Irons.
- Usually capable in section thickness between 1.5-100mm (1/16 4 in) and 30g (1oz) - 180 kg (400lb)
- Preferred in the following applications: This section casting; parts that are to be pieced, coined, or cold worked; parts requiring max machinability; parts that must retain good impact resistance at low temp; parts requiring wear resistance.





Applications

- Essential parts in trains, frames, suspensions, and wheels.
- differential cases, bearing caps, steering-gear housings, spring hangers, universal-joint yokes, automatic transmission parts, rocker arms, disc brake calipers, wheel hubs, ect...
- a) Driveline yokes, b) Connecting rods, c) Diesel pumps, d) Steering-gear housing.

Fig. 6 Examples of malleable iron automotive applications. (a) Driveline yokes. (b) Connecting rods. (c) Diesel pistons. (d) Steering-gear housing

Sample Analysis and Identification

- Possible to identify and classify a sample of unknown cast iron.
- Identification can be accomplished through the use of many known mechanical, chemical and structural properties of the cast iron alloys.
- As part of our research, we attempted to examine and identify separate cast iron samples of unknown composition.

Sample Analysis and Identification

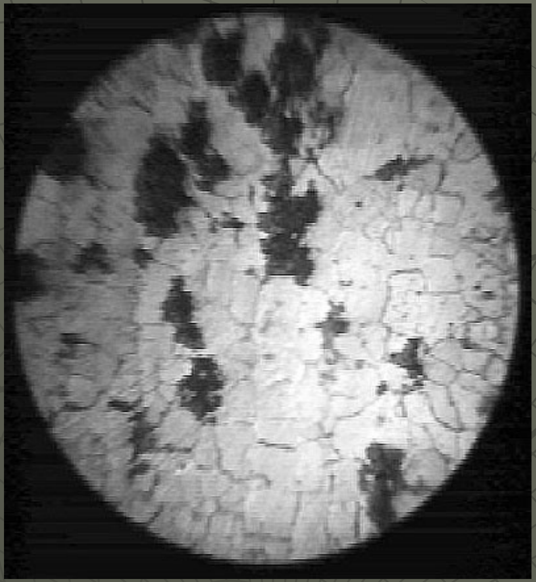
- We obtained two samples of what was initially perceived to be cast iron. The first being a cooking pot, and the second a 90° pipe fitting.
- Both samples were cut, mounted and polished in a bakelite round, for microstructure examination.
- Followed by a Rockwell hardness test of each specimen.

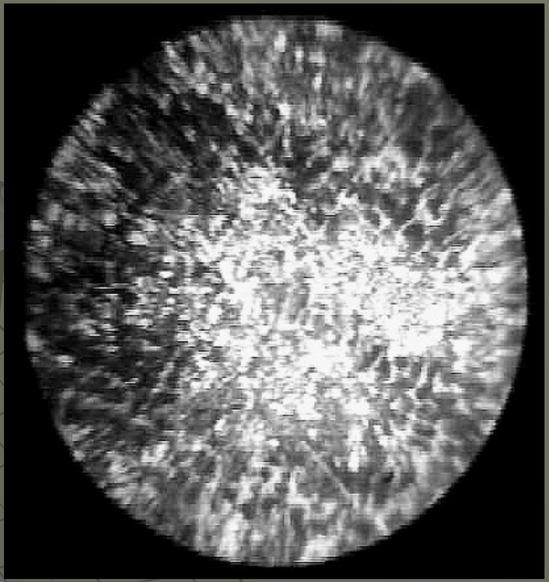
Sample Analysis and Identification

- The microstructure analysis was accomplished after polishing and etching (utilizing a 3% nitric acid solution in ethanol) to reveal the grains.

- Initially it was believed that both samples were cast irons, and although the 90° pipe fitting appears to be cast iron, the microstructure of the pot handle yielded a different conclusion.

Microstructure Analysis





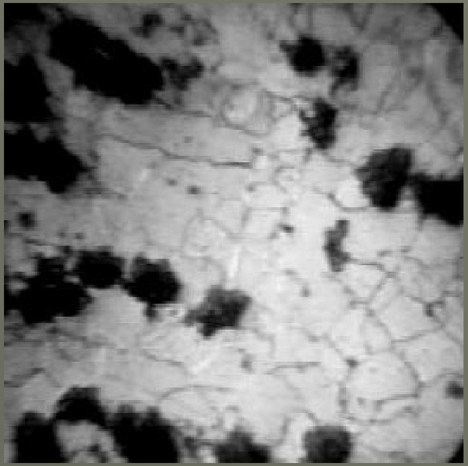
- The two micrographs are shown above, the 90° pipe fitting on the left, and the cooking pot handle on the right.
- The Rockwell hardness was also measured for both samples, yielding a hardness of 157 HRB for the fitting, and 120 HRB for the pot handle.

Microstructure Analysis

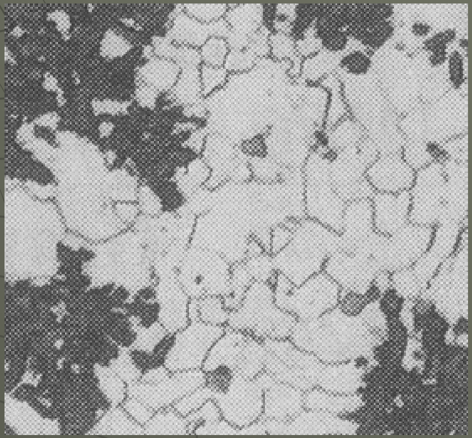
- Upon analysis of the microstructures, it became apparent that the cooking pot does not conform to any common form of cast iron.
- Although the handle fractured in a manner very similar to that of cast iron, the microstructure shows little resemblance to those of cast iron.
- Although further analysis would be required, one possibility is a cast steel material. This would account for the similarity of its fracture to that of cast iron.

Microstructure Analysis

- The 90° fitting shows indications of a dark graphite surrounded by lighter colored matrix. The graphite appears to be in the form of dark rosettes, while the matrix is a lighter color.
- Upon comparison to the known structure of different types of cast irons, it can be seen that the microstructure of malleable iron most closely matches our sample.
- To the right is a side-by-side comparison, with our sample on the top, and a known Malleable microstructure on the bottom.



Pipe Sample (150X mag)



Malleable Iron (150X mag)

Conclusion

- Cast Iron and historical significance
  - Used throughout history since its discovery, stepping stone to the development of modern technology (First Steam Engine)
- Types of Cast Irons and microstructure
  - Grays, Whites, Ductile, Malleable
- Applications
  - Automotive, Industrial, Household, Aeronautical, & Construction
- Sample Analysis and Comparison for identification and Classification
  - Capability to analyze and compare microstructures to determine Cast Iron Type. And Hardness measurements to identify heat treatment,

References

1. C.F. Walton, *Gray and Ductile Iron Castings Handbook*, Iron Founder's Society, 1971, p 193
2. C.F. Walton and T.J. Opar, *Iron Castings Handbook*, Iron Casting Society, 1981, p 235 & p 297-321
3. "Chrome-Moly White Cast Irons," Publication M – 630, AMAX, Inc., 1986
4. Davis, J.R., *Cast Irons*, ASM International, Materials Park, OH, 1996
5. G. Lambert, Ed., *Typical Microstructures of Cast Metals*, 2nd ed., The Institute of British Foundrymen, 1996, p 47
6. H.T. Angus, *Physical and Engineering Properties of Cast Iron*, BCIRA, 1960, p 21
7. http://www.msm.cam.ac.uk/doitpoms/miclib/index.php
8. http://www.matweb.com/search/GetSubcat.asp
9. http://www.wynndanzur.com/glossary.htm