# Cast Iron: History and Application

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## Abstract:

This module introduces cast iron along with its varieties and applications. Cast iron, like steel, is composed primarily of iron and carbon. However, cast iron's composition is near 4% weight carbon, which along with 1-3% weight of silicon, greatly affects the microstructure of the iron and carbon, causing graphite, a crystalline form of carbon, to form instead of cementite ($Fe_3C$). Cast iron is divided into many groups and three are touched upon in this module: gray iron with graphite flakes, ductile iron with spherical graphite, and compacted graphite iron with wormlike graphite. A discussion of properties follows and includes a hands-on activity that demonstrates the vibration damping of cast iron.

## Module Objectives:

The objective of the module is to introduce cast iron, its structures and properties. After a brief history of metallurgy, the module will explain the formation of three types of cast iron, and their benefits. Students will be able to identify types of cast iron by micrograph. Lastly, the module aims to demonstrate the material property of vibration damping through a simple qualitative test.

## Student Learning Objectives: The student will be able to

- Identify cast iron, such as cast iron cookware
- Recognize properties which make cast iron useful
- Differentiate between cast iron alloys using a microscope
- Recognize cast iron through a vibration test

## MatEd Core Competencies Covered:

7.A Identify the General Nature of Metals
7.I Explain Causes for Differing Materials Properties
9.B Define and Describe Types and Properties of Cast Iron
17.B Describe Techniques used for Metals Processing

**Key Words:** Steel, Cast Iron, Carbon, Graphite

**Type:** PowerPoint presentation with lab or in-class demonstration depending on availability of equipment

**Time required:** one class period, can include microscope viewings and vibration testing

**Suggested prerequisite:** Iron and Steel: Properties and Applications

**Target grade level:** Advanced High School, Introductory College/Technical School

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## Equipment and Supplies Needed:

- PowerPoint projection system
- Cast iron samples, such as cookware
- Cast iron microscopy samples, or micrographs (optional)
- Microscope (optional)

## Curriculum Overview

Although early civilizations could not produce fires hot enough to melt iron ore, they could heat and work the metal to remove impurities, and shape by hammering. This produced wrought iron ("wrought" meaning "worked") which mostly kept the composition of the ore with an addition of carbon from the coals during heating. If even more carbon is added and the carbon content is raised to near 4 wt %, the melting temperature drops considerably (as seen in Fig. 1) and makes melting iron feasible with early furnaces. This technique enabled early metallurgists to melt fully the iron ore and led to the first liquid iron that, cast easily into a variety of shapes, suitably named cast iron.

Usually, the carbon in steel is in the interstitial sites or used for form cementite ($Fe_3C$), a high hardness iron compound. In cast iron, the richer carbon phase facilitates graphite precipitation, a crystalline form of carbon. The advantage that cast iron has in graphite formation, instead of cementite, is not obvious at first. The graphite is considerably weaker than cementite and weaker than the iron around it, acting essentially as voids in the material, weakening the metal and reducing ductility. The graphite flakes do offer non-mechanical advantages, such as vibration damping and wear resistance, along with being extremely cheap to produce.

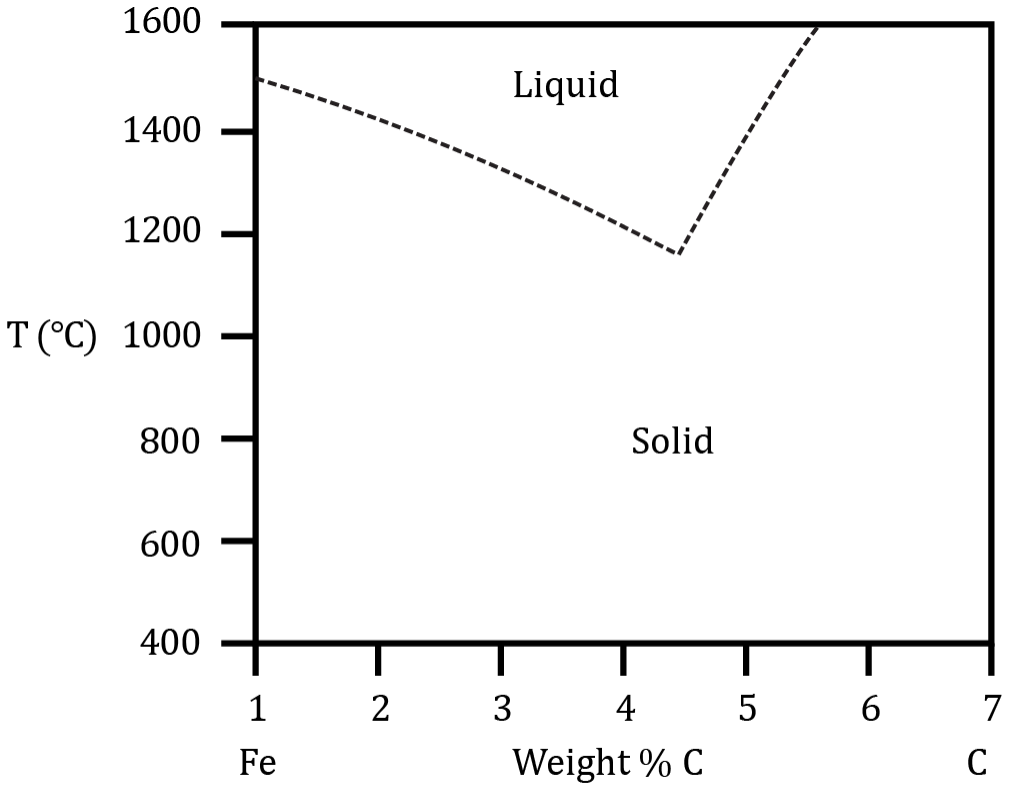


**Figure 1: Fe-C phase diagram with the dotted line showing melting temperature. Notice the lower melting temperature of the liquid (L) as the carbon content increases, to about 4.5 wt percentage C.**

In addition to the high carbon content, a 1-3% weight silicon added to the iron increases the potential for graphite formation, or graphitization. The presence of silicon also increases the fluidity of the liquid, which improves castability. As cast iron techniques improved, other added alloying elements made cast iron stronger or more durable, while retaining its desirable characteristics. Elements such as magnesium, phosphorus, and cerium could be added for a variety of reasons but may decrease graphitization potential, which may necessitate the need for more elements to create a balance for graphite formation.

**Types of Cast Iron**

The physical shape of carbon in the iron matrix primarily determines the type of cast iron. Various types of cast iron were developed and extensive effort was made to influence the shape of the graphite in the cast iron by alloying, and heat treatment was used to alter the steel microstructure to improve mechanical properties. The various types developed each have unique and specific commercial applications.

The shape of the graphite also determines the mechanical response of the cast iron. Since the graphite is essentially a void, the stress concentration calculates like an elliptical crack, given the formula:

$$\sigma_c = \sigma_0 \left(1 + 2\frac{a}{b}\right)$$

where $\sigma_c$ is stress at the crack tip, $\sigma_0$ is stress applied, and $a$ and $b$ are length and width of the crack, respectively. This formula comes down to this: as $a$ increases relative to $b$, stress concentrations at the crack tip also increase, and a higher stress concentration will allow crack propagation. One can qualitatively estimate mechanical response for each type by comparing graphite geometry. Inversely, a cast iron's vibration damping properties increase with stress concentration.

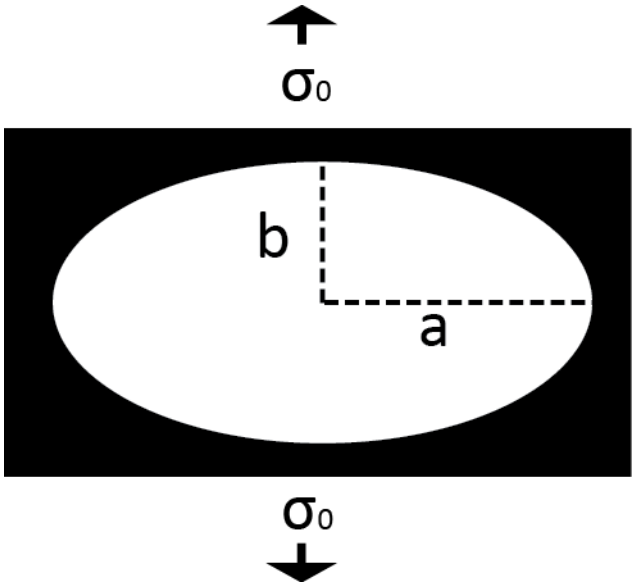


**Figure 2: Crack tip geometry affects stress at the crack, depending on *a* and *b* of the crack.**

## Gray Iron

Historically, the first type of cast iron was gray iron, named for its gray color on the fracture surfaces. It is also the cheapest cast iron to produce. When graphite forms in gray iron, it produces flakes with sharp points within the iron matrix, such as seen in figure 2. These sharp points lead to stress concentrations, like a sharp notch in a beam**.** As a crack forms, it will travel through these graphite flakes, and due to the flakes' sharp points, continue to travel with ease. Due to this nature, the focus of gray iron engineering is on castability rather than mechanical properties.

**Figure 3: A gray iron micrograph at 100x magnification. The points at the end of the flakes allow cracks to move through the metal.**

While gray iron is full of graphite flakes, it is still a strong material, especially in compression, and a high melting temperature. Gray iron is very resistant to wear and excellent at damping vibrations. This is extremely useful in construction, heavy machinery, and vehicle parts such as brakes, where vibration damping and heat resistance are most important.

### Ductile Iron

Instead of producing flakes like gray iron, ductile iron produces spherical graphite particles (figure 3) which lower stress concentrations, leading to a stronger and more ductile cast iron. When a crack propagates through ductile iron, the crack will meet a piece of spherical graphite and the crack tip will be rounded out, impeding crack growth, which makes it considerably more ductile than gray iron, and even close to the mechanical properties of regular steel. The strength of ductile iron makes it preferred for structural applications involving cast iron such as bridges and useful in machinery where brittle gray iron parts may fail.

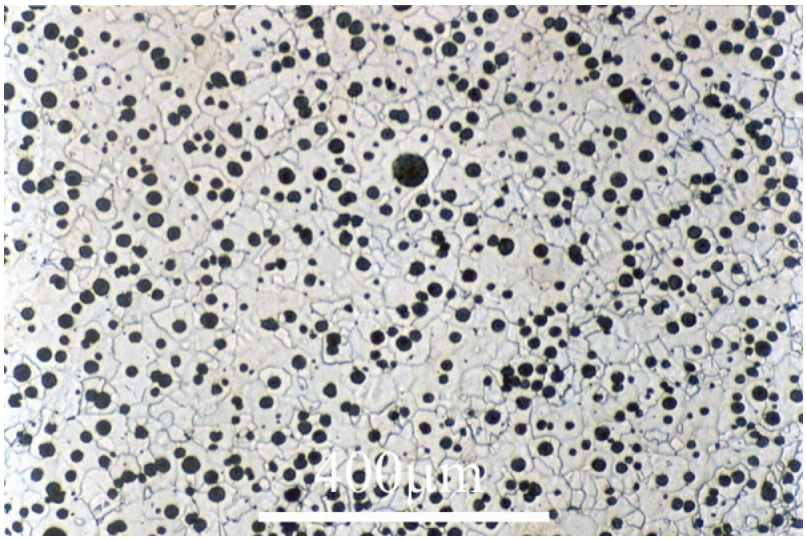


**Figure 4: The nodule structure of the graphite in ductile iron eliminates any sharp points from the graphite, slowing crack propagation.**

Adding magnesium (Mg) or cerium (Ce) in amount less than 0.1% facilitates the growth of the graphite spheres. If cementite does form, pearlite is often found in the surrounding iron matrix. Since cementite is brittle and the idea of ductile iron is to be ductile, the iron can be heat treated to turn the pearlite into ferrite, making ductile iron more ductile at the expense of hardness. This flexibility in strength combined with damping properties allows ductile iron to be very versatile in application.

### Compacted Graphite (CG) Iron

While gray and ductile iron have been around for many centuries, compacted graphite (CG) iron is a newer product, first produced around 1950. In terms of microstructure, graphite exists as rounded wormlike structures (figure 4), effectively combining the flake structure of gray iron with the rounded edges of ductile iron. These structures can be achieved through a complex addition of trace elements similar to ductile iron such as magnesium, cerium, and titanium. CG iron can also be heat treated to alter the iron around the graphite, similar to ductile iron.

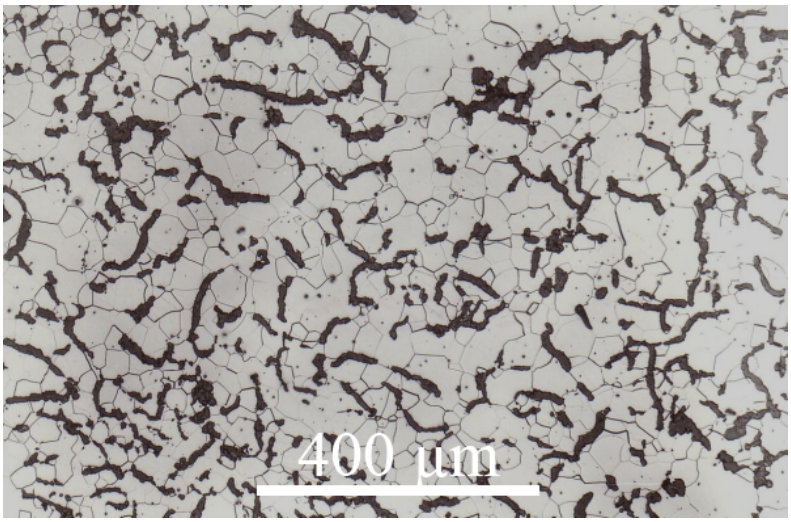


**Figure 5: CG iron's wormlike structure mixes the long flakes of gray iron with rounded edges of ductile iron.**

The wormlike graphite will also reduce crack tip size, such as in ductile iron, but may intercept cracks more often due to the larger graphite formations. In addition, CG iron also has the advantages of a higher thermal conductivity and better thermal shock reduction than ductile iron. CG iron has found a home in diesel engines, where higher pressures are attained during combustion thanks to CG iron's strength, and with less weight when compared to traditional gray iron diesel engine parts.

## Hands-On with Vibration Damping

Excessive noise and high vibration are inherently associated with equipment used in the mining, extraction, and processing of mineral resources. High vibration degrades structural components, often leading to catastrophic failure and loss of productivity, and excessive noise results in permanent hearing loss.

For an experiment to measure vibration damping quantitatively, one would need expensive equipment and advanced calculus. However, the human body has one built in mechanism for detecting vibration: ears. Vibration makes sound that you can hear, and something that dampens vibrations should not make sound for a long duration of time. For this experiment, loosely hold pieces of cast iron, stainless steel, and perhaps other metals, such as cookware, and hit them gently with a metal hammer and listen to the duration of the ring.

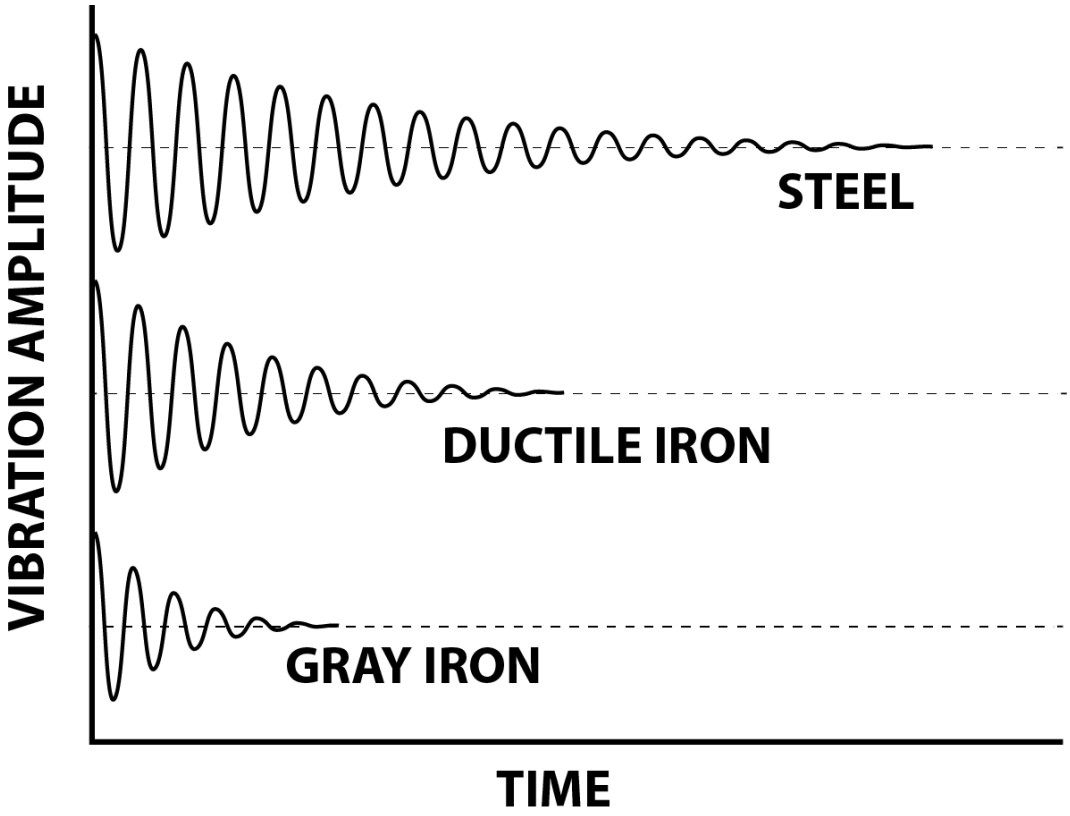


**Figure 6: Vibration as a function of time for steel, ductile iron, and gray iron.**

**Module Procedure:**

1. Discussion
    a. What are some material properties other than mechanical strength? Which materials have these properties? Sample answers include electrical conductivity of copper or corrosion resistance of stainless steel.
    b. Present a cast iron brake caliper. Ask the students if they know what material it is. What material properties would this part benefit from? Vibration damping, mechanical strength.
2. Present the slideshow to the students
    a. Identify the parts of the Fe-C phase diagram as shown in figure 1. Ask students to identify the importance of 4% carbon, pointing to the lower melting temperature.
    b. Ask the students if they know about the mechanical properties of graphite. Mechanical pencil graphite can be broken to illustrate that it is weak. How does this affect the strength of cast iron? How does this compare to iron? It clearly weaker.
    c. Introduce or reintroduce the idea of stress concentration – show the picture and stress formula, and show that by increasing the crack radius ($a$), the

stress concentration increases; deriving or explaining the whole formula is unnecessary

**d.** Show the grey iron micrograph, pointing out the dark graphite structure against the white iron matrix. Point out the flake-like structure, focusing sharp tips.

**e.** Grey iron crack geometry – *a* is much larger than *b*, which leads to high crack tip stress.

**f.** Introduce the idea of a cast iron that has ductile mechanical properties. What has to happen? The crack radius has to decrease, which happens with spherical graphite formation. Show the ductile iron micrograph and the graphite spheres.

**g.** Retouch on the stress concentration with the sphere stress diagram

**h.** Show the micrograph for compacted graphite iron. What are some observations about the graphite formation? Point out both rounded edges and long structures. This effectively combines graphite structure from grey and ductile iron. This is referred to as a vermicular, or "wormlike", graphite formation. What are the properties of combining the two? Properties somewhere in the middle along with improvements of combining the two.

**i.** For cast iron in general, vibration damping is an important property. Most metals vibrate a lot (even used for musical instruments, such as a triangle), so a material that is as strong as a metal but able to dampen vibrations would have plenty of applications. Applications include brake calipers, which hold the brake pad, and motor mounts. What other application would there be for vibration damping metals? (**heavy machinery base, drills, early bell holders)**

j. Metals have a characteristic known as 'damping capacity'. Check out the following graph to see a sample of vibration. The all three metals produce the same initial vibrations but notice the difference as time goes on.

**3.** Vibration damping demonstration

**a.** Explain that vibrating metal produces sound, showing this with perhaps a triangle or a piece of steel hit. Given the previous slides, ask the students what will happen with the cast iron.

**b.** Hit the cast iron and compare it to non-cast iron samples. How do they compare? This can be done qualitatively or use a stopwatch, measuring each materials vibration duration. **(Note, each sample may have different characteristics such as shape and handle which may not produce desired quantitative results.)**

**Supporting Materials for Further Reference**

- "New Science of Strong Materials" by J.E. Gordon. Princeton University Press, 2006.
- "Structures or why things don't fall down" by J.E. Gordon. Da Capo Press, 2002.
- Cast iron – http://www.wikipedia.com/wiki/Cast_iron


## Evaluation

### Student evaluation (discussion/quiz)

1. What addition enabled iron ore to be fully melted? Which other element is added to facilitate casting and improve graphitization?
2. Which material property determines the name and mechanical response of each cast iron?
3. How does graphite form in each type of cast iron? Does a sharper point in graphite formations lead to a higher or lower stress concentration?
4. How is vibration damping a desirable trait?
5. How does the sound of cast iron pieces compare to those of other metals?

### Student Activity

1. Find one or two pieces of cast iron in your daily life. What purpose does it serve? Does it benefit from vibration damping?

### Instructor evaluation

1. What grade level and class was this module utilized for?
2. Were the students able to grasp the key concepts introduced in the module?
3. Was the level and rigor of the module acceptable for the grade level of the students? If no, how can it be improved?
4. Was the demonstration/lab work as outlined? Did it help the students in learning the material? Were there any problems encountered?
5. Was the background on iron and stress sufficient for your understanding and for the discussion with the students?

Any comments and/or suggestions on improving this module are encouraged.

### Course evaluation questions

1. Was the demonstration/lab clear and understandable?
2. Was the instructor's explanation comprehensive and thorough?
3. Was the instructor interested in your questions or concerns?
4. Was the instructor able to answer your questions thoroughly and to your satisfaction?

**Acknowledgments**

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