

# Allotropes of Iron

## Structures of Solids



## Introduction

Heat treatment of metals is used to increase their hardness and their “workability”—their ability to be bent and shaped. Annealing, hardening, and tempering are examples of changes that occur in the physical properties of metals as they are heated and cooled. The changes are related to the crystal structure of the metal.

## Concepts

- Properties of metals
- Body-centered cubic vs face-centered cubic
- Crystal structure
- Allotropes

## Materials

Bunsen burner or propane torch  
Beaker, 250-mL  
Crucible tongs

Heat-resistant pad or wire gauze  
Paper clips, 16  
Water, tap

## Safety Precautions

*Exercise care when working with hot metals. Wear chemical splash goggles and heat-resistant gloves whenever working with heat, chemicals or glassware in the lab.*

## Procedure

1. Ask students to describe the properties of the metal in a paper clip. Determine the average number of times a paper clip can be bent back and forth before it will break. *(On average, a paper clip will break after it has been straightened out and rebent seven times.)*
2. Hold the ends of a paper clip with crucible tongs. Heat the bend of the paper clip in a burner flame until the metal is red hot. Place the paper clip on a heat-resistant surface and allow it to cool to room temperature. Repeat if desired to obtain several samples for testing.
3. Test the properties of the metal: Count the number of times the treated paper clip can be bent back and forth before breaking. *(The treated paper clips are easier to bend but more difficult to break—the treated paper clips can be bent back and forth about 12 times before breaking.)*
4. Steps 2 and 3 represent the *annealing* process. Define annealing. *(Annealing is the process of strong heating followed by slow cooling. Annealing softens a metal and makes it less brittle.)*
5. Hold the ends of a paper clip with crucible tongs and heat the paper clip in a burner flame until it is red hot. Immediately drop the paper clip into a beaker filled with cold water. Repeat if desired.
6. Remove the paper clips from the water and dry them. Test the properties of the metal: Count the number of times the treated paper clips can be bent back and forth before breaking. *(The paper clips are extremely hard to bend but break easily—on average, the paper clips break on the first try!)*
7. Steps 5 and 6 represent the *hardening* process. Define hardening. *(Hardening is the process of strong heating followed by “quenching” or rapid cooling. Hardening makes a metal very rigid and brittle.)*
8. Heat a paper clip until it is red hot, then drop it into cold water to cool it quickly. Dry the paper clip and *gently* reheat the paper clip by holding it above a burner flame until it acquires a blue oxide coating. Place the paper clip on a heat-resistant surface and allow to cool to room temperature. Repeat if desired.
9. Test the properties of the metal: Count the number of times the treated paper clips can be bent back and forth before breaking. *(The paper clips are hard but “springy”—they do not break.)*

10. Steps 8 and 9 represent the *tempering* process. Define tempering. (*Tempering is the process of strong heating and rapid cooling followed by gentle reheating and slow cooling. Tempering reduces the extreme hardness of the metal but increases its “toughness.” The tempered metal is nonbrittle.*)

## Disposal

Please consult your current *Flinn Scientific Catalog/Reference Manual* for general guidelines and specific procedures governing the disposal of laboratory waste. Used paper clips may be disposed of in the trash according to Flinn Suggested Disposal Method #26a.

## Tips

- Refer to the discussion of metal crystal structure to explain the properties of metals. Models of face-centered cubic (FCC) and body-centered cubic (BCC) crystal structures will help students visualize the changes that are observed. The “Cubic Unit Cell Model” available from Flinn Scientific (Catalog No. AP7037) is a versatile super-size model and a valuable teaching aid for demonstrating crystal lattice structure.
- Metals that crystallize in the BCC crystal structure include vanadium, chromium, manganese, iron, and all of the alkali metals. Metals that crystallize in the FCC crystal structure include aluminum, lead, copper, silver, and gold.
- The FCC structure is an example of “closest packing” of solids—identical atoms are packed as closely as possible into a given space. If one assumes that the atoms behave as small spheres, the atoms occupy 74% of the volume of the FCC crystal structure and have a coordination number of 12. This is the maximum coordination number and maximum density possible for atoms in a solid lattice composed of small “spheres.”

## Discussion

An allotrope is a distinct arrangement of atoms of one element—graphite and diamond are two allotropes of carbon, for example. Likewise, iron has four allotropes, three of which are explored in this demonstration. Paper clips are made of steel—iron that has been alloyed with about 1% carbon to improve its hardness and toughness. Heat treatment affects the crystal structure of the metal. At room temperature, steel crystallizes in a body-centered cubic (BCC) structure called *alpha*-ferrite. This BCC structure does not dissolve carbon and is soft and ductile. Heating the BCC form transforms it into a face-centered cubic (FCC) crystal structure that dissolves carbon and is very hard. Sudden cooling of the high-temperature FCC structure by quenching it in water (hardening) causes the dissolved carbon atoms to become trapped in the BCC lattice. The resulting stress and distortions in the crystal structure make the metal extremely hard but also very brittle. This form of iron is called martensite. Slow cooling of the high-temperature FCC structure (annealing) allows the iron to crystallize in the stable BCC form and the carbon to precipitate out in the form of large particles that cause minimal disruption or dislocation of the crystal structure. The result is a soft, nonbrittle, very workable form of the metal. Gentle reheating of the hardened form followed by slow cooling (tempering) allows the trapped carbon to precipitate and removes many of the internal stresses in the distorted martensite crystal structure. This reduces the extreme hardness of the metal but also eliminates the brittleness. The tempered metal is very strong yet still “workable.”

## Connecting to the National Standards

This laboratory activity relates to the following National Science Education Standards (1996):

### ***Unifying Concepts and Processes: Grades K–12***

Evidence, models, and explanation  
Constancy, change, and measurement

### ***Content Standards: Grades 9–12***

Content Standard A: Science as Inquiry  
Content Standard B: Physical Science, structure and properties of matter, conservation of energy and increase in disorder, interactions of energy and matter  
Content Standard F: Science in Personal and Social Perspectives, science and technology in local, national, and global challenges  
Content Standard G: History and Nature of Science, science as a human endeavor

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## Flinn Scientific—Teaching Chemistry™ eLearning Video Series

A video of the *Allotropes of Iron* activity, presented by Jamie Benigna, is available in *Structures of Solids*, part of the Flinn Scientific—Teaching Chemistry eLearning Video Series.

## Materials for *Allotropes of Iron* are available from Flinn Scientific, Inc.

Catalog No.	Description
AP5344	Bunsen Burner, Adjustable, Natural Gas
AP8266	Crucible Tongs
AP1188	Wire Gauze, Square with Ceramic Center

Consult your *Flinn Scientific Catalog/Reference Manual* for current prices.