Materials Science Mini Kit: Does Heating a Nail Make it Harder?

Lesson Plan: Overview and Safety

Lesson Objective

To demonstrate the effects of heat treatment on a metal's physical properties by examining the differences in hardness and ductility between untreated and annealed aluminum nails.

Experiment Description

This experiment demonstrates the changes in mechanical properties of a metal material after undergoing heat treatment. Two aluminum nails, one untreated and one annealed, will be dropped and deformed. The sounds the two nails make, the height to which they bounce, and the ease with which they bend or fail will be compared. Because increasing temperature promotes grain growth, the annealed nail will have larger grains and thus be softer than the untreated nail.

Materials List

Items provided in the kit

- 1 untreated aluminum nail
- 1 annealed aluminum nail

Items to be provided by the teacher/school

- pliers
- safety glasses

Optional items for extending the experiment

- hammer
- wooden block
- other types of nails (e.g., iron, steel)
- other tools for inspecting nail performance

Safety Precautions

Nails are **sharp**

- Nails should not be handled by young children.
- Nails should be handled carefully and not tossed or thrown; nails should be dropped as described in the experimental procedure.
- Safety glasses are recommended for all active participants.

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Lesson Plan: Background Information

Metallurgy

History

The discovery of metallurgy marked a significant turning point in human history. The use of metal tools and weapons allowed early humans to improve their hunting, farming, and construction techniques, which were previously based on stone and wooden tools. This was one technological factor that assisted the development of complex societies and civilizations.

The field of metallurgy began to evolve and formalize during the Industrial Revolution in the 18th and 19th centuries. Innovations in manufacturing and transportation led to an increased demand for metals with specific mechanical properties, such as increased strength and durability, and chemical properties, such as improved corrosion resistance. Today, metallurgy plays a crucial role in a wide range of industries, including aerospace, automotives, biomedical engineering, electronics, and many others.

One of the oldest and still most heavily-used metallurgy processing techniques is heat treatment. Two otherwise identical metal objects can behave very differently simply based on how they were heat treated. To make a metal material useful for a specific task, metallurgists control the temperature to which they heat it, how long it is held at specific temperatures, when during the manufacturing process the heat is applied, and how quickly the material is heated or cooled. These different processing steps cause the metal to have different properties depending on the heat treatment parameters.

How Does Heat Treatment Change a Metal?

Metals are crystalline solids, which means they have long-range atomic scale ordering where atoms or molecules appear in regular, repeating patterns. There are many ways to alter how crystals form. In much the same way that ice crystals can freeze to form different shapes of snowflakes, metal crystals can form different shapes. Most materials are made of many, many crystals connected together to form microstructures. One of the simplest ways of changing the microstructure of a metal involves heating or cooling the material to produce a desired size and shape of crystals. These microstructures can determine important properties for the material as a whole. One crystal structure will make a metal soft and pliable, while another microstructure makes the material hard and strong. The material itself is unchanged in that nothing is added or removed. Only the arrangement of the atoms or molecules and the shapes of the crystals already inside the material change.

Each crystalline microstructure has a specific temperature range where it will nucleate new seed crystals (i.e. begin to form tiny solid particles out of a liquid) and a specific temperature range in which seed crystals grow (the smallest crystals dissolve and their atoms join the larger crystals, which become even larger). If the metal is heated too high and begins to melt into a liquid, the microstructure will "reset," and a new microstructure will be created in the material as it cools back down to a solid. This resetting of the microstructure can be very useful. For example, metallurgists can forge or cast a part into a desired shape, then heat treat it according to a specific series of steps to modify the microstructure and produce a final product with specific desirable properties.

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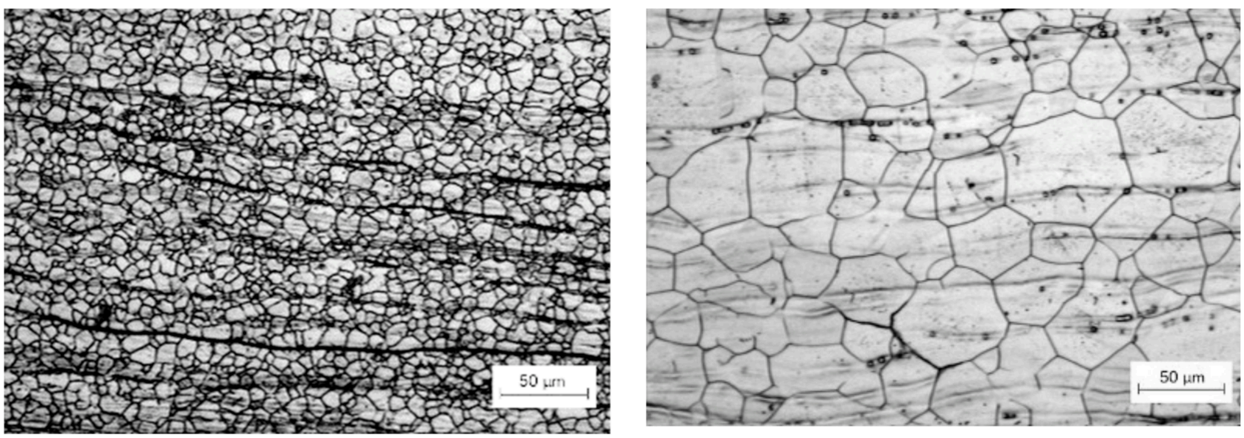
Lesson Plan: Background Information

Two common types of heat treatment are annealing and quenching. Annealing is a heat treatment designed to relieve stress within a material through a very slow cooling process. The material spends an extended period of time at higher temperatures, which gives the crystalline structure time to rearrange itself or reset. An annealed metal will be softer and more ductile (or flexible).

Quenching is a heat treatment where nearly-molten metal is cooled rapidly by dunking it in much cooler fluid, such as a liquid, like water or oil, or a gas, like air, argon, or nitrogen. Because the metal is cooled very quickly, the crystalline structure has very little time to rearrange itself. Quenched metal is typically very hard and will not easily change shape, but it can also be brittle (not flexible) because of this heat treatment. Neither treatment method is "better" than the other; they are simply each better suited for different applications and are often used together. For example, a metal might be heated to a high temperature so that it can be formed into a specific shape, quenched so that it will keep that shape, then annealed at a medium temperature to relieve internal stress. The "correct" heat treatment processing steps depend on how the material will be used.



(a) (b)

Figure 1. Microscopic view of the same steel subjected to different heat treatments. Notice the difference in particle size and shape. The microstructure pictured in (a) has small crystals that were not allowed enough time to grow, which suggests that the material was quenched. This material will be harder and stronger but more brittle. The microstructure pictured in (b) has larger crystals that were allowed time to grow, which suggests that the material was annealed and cooled slowly. This material will be softer and weaker but more ductile.

Keywords

annealing: a heat treatment process that involves heating a material to a high temperature then cooling it slowly to improve certain properties, such as increasing ductility or malleability. Annealing can also occur when a material is heated to a medium temperature and held for a long period of time (often hours or days, depending on the material and desired microstructure or properties).

crystalline solid or ***crystal***: a material with long-range atomic scale ordering in which atoms or molecules appear in regular, repeating patterns. Examples include: ice, table salt, sugar, metals, faceted gemstones, diamond, and graphite.

deformation strength: the maximum amount of elastic (reversible) stress a material can withstand, before plastic (permanent, irreversible) deformation occurs. This is also known as the yield strength or elastic limit.

elastic deformation: deformation of a material that does not permanently change its shape; the material *will* return to its original form. Examples of materials undergoing elastic deformation include stretching a rubber band or slinky, which return to their original shapes when released. If the material is stretched beyond its elastic limit, it may become permanently deformed or fail (break).

metallurgy: a branch of materials science and engineering that focuses on the study of metals, their properties, and techniques for extraction, processing, and manufacturing. It involves the study of the physical, chemical, and mechanical properties of metals, as well as their behavior under different conditions and in different environments.

plastic deformation: deformation of a material that permanently changes its shape; the material *will not* return to its original form.

quenching: a heat treatment process involving rapidly cooling a material from an elevated temperature to a low temperature, typically room temperature or below, by submerging the material into a fluid (such as a gas, like air, argon, or nitrogen, or a liquid, like water or oil). Quenching can lock-in the crystal structure of a material by not allowing time for atoms and crystals to rearrange, which will determine the material's properties.

stress: the force per area exerted on matter, measured in units of pressure. Materials experience *internal stress* when atoms or molecules within the material are arranged in unfavorable ways. For example, if atoms or molecules along the border between two adjacent crystals do not line up, their atomic bonds may be stretched or squished, giving rise to internal tension or compression.

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Lesson Plan: Teaching Instructions

Experimental Procedure

1. Drop the untreated nail onto a hard surface.
2. Estimate how high the nail bounces and describe the sound it makes.
3. Repeat for the annealed nail.
4. Compare the bounce heights and sounds of the two nails.
5. Attempt to deform the untreated nail via one or more methods.
   Method 1: Use pliers (or fingers) to bend the nail.
   Method 2: Use a hammer to drive each nail into a wooden block.
6. Repeat for the annealed nail.
7. Compare how easy it was to bend the nails.

Cleanup and Resupply

- Ensure all nails are put away.
- If using the wooden block, remove nails and clean wood splintering off surfaces.

Tips for Success

- Depending on the age group, this activity can be done in small groups or with everyone watching the teacher do it.
- The annealed nail can often be bent by hand, but the difference is much easier to demonstrate with a tool.
- Be careful not to accidentally bend the annealed nail prematurely (e.g. while inspecting the materials before actually conducting the experiment).
- Encourage students to predict and explain why they expect certain outcomes.

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Lesson Plan: Discussion Prompts

Before the Experiment

Compare the untreated and annealed nails (color, shininess, apparent weight, surface texture, softness, coolness-to-touch, etc.). Do they look or feel different? **Caution!** *The annealed nail will bend under fairly low force, so avoid deforming it prematurely.*

Which nail (untreated or annealed) do you think will be harder and why?

Hardness is related to microstructure, particularly grain size, with hardness increasing as grain size decreases. The annealed nail will have larger grains because they will have grown larger while the material was at elevated temperatures.

Predict whether the annealed nail will make the same sound or different. If different, in what way? Why?

During the Experiment

Describe the sound made by each nail as it hit the hard surface.

The (weakened) annealed nail will sound dull while the untreated nail will sound sharp and clear.

Why does the annealed nail sound so much different from the untreated nail?

Both nails gain kinetic energy as they fall to the surface. When they strike the surface, some of their energy is converted into sound. Since the annealed nail is softer, it loses some energy as it deforms from the impact, so it has less energy available to release as sound. The untreated nail is too hard to be deformed, so energy is released through sound.

Compare how easy or difficult it is to deform the untreated and annealed nails.

It is easy to bend the annealed nail, but difficult to do the same thing to the untreated nail. Likewise, the untreated nail will perform exactly as a nail is expected to when hammered, while the annealed nail will likely bend rather than penetrate the wood.

After the Experiment

What are different applications for which each type of metal (harder or softer) would be useful

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Student Handout

1. Describe the untreated and annealed nails. Do they look (color, dullness) or feel different?
2. Describe the sound each nail made when dropped onto a hard surface. Did they sound the same? Did they behave the same way after hitting the surface?
3. Which nail, untreated or annealed, absorbed more energy? How can you tell?
4. What are some applications for which we want a material to absorb *more* energy when impacted? What are some applications for which we want a material to absorb *less* energy when impacted?
5. Describe how each nail behaved when it was bent with the pliers (or fingers) or hammered into a wood block. Did they behave the same?
6. Which nail, untreated or annealed, was harder?
7. What are some applications for which harder metal would be useful? What are some applications for which softer metal would be useful?
8. How can we turn each type of nail into the other? (Hint: it is done through steps of heating and cooling at different rates.)