TEACHER INSTRUCTIONS

Fun with Liquid Nitrogen

Objective: To demonstrate the effects of temperature on the mechanical properties of materials by observing that many objects which are soft and malleable at room temperature become brittle when they are very cold.

Background Information: There are many real-world applications that put our understanding of the effects of temperature on materials to good use. A very well-known example is that of the Liberty ships, a type of cargo ship produced in large numbers by the United States during World War II. Many of the early ships used a variety of steel which became brittle and could crack at lower temperatures. Unfortunately, the cold water of the North Atlantic Ocean was below the temperature at which the steel became brittle, and as a result, a number of ships literally cracked in half! Another application for which temperature is important to consider is in turbine blades of jet engines. Jet engines burn fuel at such high temperatures that most normal metals would melt or become soft during operation. Therefore, jet engines that run at the highest temperatures often use ceramic turbine blades because they can better withstand the high temperatures without becoming warped or flexible.

Demo Description: In this demonstration, students will learn the difference between how some common items act at room temperature versus how they act after having been submerged in liquid nitrogen for a short time.

Keywords:
- temperature: a quantity which indicates how hot or cold a material is
- brittle: a material that breaks with little deformation when subjected to stress
- ductility: a solid material's ability to deform under tensile stress
- elasticity: the ability of a material to deform when loaded and then return to its original shape upon unloading
- plasticity: refers to the ability of a material to undergo permanent deformation without breaking

Materials List:
- liquid nitrogen
- styrofoam bowl (or some other well-insulating container)
- marshmallows
- rubber bands

· ping-pong balls
· sewing needle
· tongs
· insulating gloves
· safety glasses
· broom and dustpan
· hammer (OPTIONAL)

Safety Precautions: Liquid nitrogen is a hazardous substance. If misused, it may cause frostbite, eye damage, torn flesh, or asphyxiation. **ALWAYS FOLLOW THESE SAFETY RULES:**

- Keep liquid nitrogen away from students.
- Wear safety goggles at all times.
- Use tweezers to handle superconductors, magnets, or other small, cold objects. Plastic tweezers are desired but should be tested for embrittlement (see last caution) before use in the classroom.
- Wear insulating gloves when handling liquid nitrogen containers or large, cold objects.
- Use liquid nitrogen only in well-ventilated places.
- Do not allow liquid nitrogen to touch any part of your body.
- Items in contact with liquid nitrogen become **EXTREMELY COLD**. Do not touch any item that has been immersed in liquid nitrogen until it has warmed to room temperature.
- Do not store liquid nitrogen in any container with a tight-fitting lid. A tightly sealed container will build up pressure as the liquid boils and may **EXPLODE** after a short time.
- Many substances become brittle and may shatter when cold, sending pieces of the material flying. Avoid common glass and large, solid plastics.

Instructions:

1. While wearing gloves, pour some liquid nitrogen into the styrofoam bowl.
2. Submerge a rubber band in the liquid nitrogen for about one minute.
3. Remove the rubber band and hold it at one end with the tongs. Ask that a student put on a glove and attempt to stretch it. Observe that it snaps in a brittle manner.
4. Repeat step 2 with a marshmallow.
5. Remove the marshmallow. Drop it on the floor and observe it shatter.
6. Very carefully puncture a ping pong ball with the sewing needle and repeat step 2.
7. Remove the ping pong ball and place it on the floor or table. As the air inside warms back to room temperature, it expands and releases from the small hole, causing the ball to spin.

Demo Delivery Hints: The above items were chosen primarily due to their low cost and their ability to demonstrate some key mechanical property changes in materials. Feel free to augment the recommended items with others of your choice. Additional objects of interest might include fruit (such as grapes or bananas), flowers, or balloons inflated with air. The latter can be used to show the remarkable volume change experienced by a gas over a temperature range. You could also use the ideal gas law to quantify that volume change.

Troubleshooting: If the objects dropped to the floor do not shatter readily, a hammer can be used to shatter the objects. Place the objects on a hard surface that will not be damaged by the hammer and take extra precautions with finger and eye protection.

Cleanup/Replacement parts: Dispose of the liquid nitrogen by either letting it boil away completely, or for a bit more excitement, pour it carefully onto the floor where the liquid will form small spheres that will scatter and dissipate quickly. Make sure the shattered objects have warmed to room temperature, and then use the broom and dustpan to sweep up the pieces.

TEACHER DISCUSSION QUESTIONS

Fun with Liquid Nitrogen

Discussion Questions to Ask Before the Demo

1. Ask students to give examples of how materials deform when a force is applied to them.

   Discussion: Materials generally deform in one or both of two ways: in an elastic manner or a plastic manner. Perfectly elastic materials, like rubber bands at room temperature, can be deformed (stretched) by a force, but will return to their original shape when the force is removed. Perfectly plastic materials, like silly putty at room temperature, change shape when a force is applied and remain in that shape even after the force is removed. Most materials deform in a way that is a combination of the two. For example, squish a fresh marshmallow. It will flatten out because of the force applied by your fingers. When you stop applying the force, you may notice that the marshmallow tries to puff back to its original shape, but it doesn't quite get there. The marshmallow's attempt to puff back to its original shape is the elastic component of its deformation, while the leftover flattening is the plastic component of its deformation.

2. Ask students to give examples of how materials break.

   Discussion: Materials generally break in one or both of two ways as well: in a brittle manner or a ductile manner. In a 100% brittle material, such as a coffee mug, the constituents of the material (atoms in the case of a coffee mug) cannot rearrange themselves easily when a force is applied and therefore the bonds between them fracture. In a 100% ductile material, like silly putty, the constituents of the material (polymer chains in the case of silly putty) can easily slide over one another and eventually the material stretches so thin that no more material is left to slide over itself, and it becomes two pieces. As with deformation, most materials break in a way that is a combination of the two. If you pull a marshmallow fast enough at room temperature it will stretch some as the sugar molecules slide over one another, but it will then “snap” in two. The stretching is the tendency of the marshmallow to break in a ductile manner, while the “snap” is the tendency of the marshmallow to break in a brittle manner.

3. Ask students how they think changing temperature will affect how materials deform and break.

   Discussion: When discussing how materials break, it was noted that brittle materials are brittle because the constituents of the material cannot rearrange. What factor determines the ease of that rearrangement? Temperature is the answer in most cases. Temperature is a measure of thermal energy, which in turn is essentially how much and how fast atoms in the material vibrate back and forth. When a force is applied to a material, the material's thermal vibrations can let the material's constituents hop or slide over each other, allowing for plastic deformation and a tendency towards breaking in a ductile manner. For the same reason, a material with less thermal energy cannot as easily let its constituents hop or slide, so the material has a tendency towards breaking in a brittle manner. So, you would probably expect materials to become more brittle as the temperature decreases.

4. Ask students why it is important for engineers to think about temperature when selecting materials for specific purposes.

   Discussion: See the Background Information section in the Teacher Instructions for discussion of this question.

Discussion Questions to Ask During the Demo

1. Ask students to guess how each object will behave before subjecting the object to a test.

   Discussion: There is no right or wrong answer to this question. Encourage as much discussion as possible as this is the best way to get students interested in the demo.

2. Ask students to note how each object behaves or breaks after testing.

   Discussion: See the explanation of brittle/ductile and elastic/plastic and the influence of temperature discussed in Questions 1-3 above. Encourage students to make the connection about the change in material properties (e.g., moving from ductile to brittle when exposed to liquid nitrogen, elastic to plastic, etc.) that they observe when a material is subjected to liquid nitrogen.

Discussion Questions to Ask After the Demo

1. Ask students to compare the behaviors of the rubber band at room temperature versus at 77 K.

   Discussion: Both objects break in a very brittle manner because neither has enough thermal energy to plastically or elastically deform (only small atomic scale deformations occur). At room temperature, rubber bands can stretch because they are comprised of coiled polymer chains (like springs) that uncoil and recoil when a force is applied and removed. At 77 K, the polymer coils do not have enough thermal energy to uncoil themselves. Therefore, only the bonds between individual atoms in the polymer chains can stretch. The bonds between each polymer chain are much weaker than the bonds between atoms, resulting in the rubber band breaking as soon as the forces on the chains exceed the chain-chain bond strength. Interestingly, the rubber band still deforms elastically, but only the smallest amount on the atomic scale rather than on the larger chain scale. Ceramic materials behave similarly. Most people do not consider ceramics to be elastic, but in general, ceramics can ONLY deform elastically. The deformation from stretching atomic bonds in ceramics requires large forces and results in such little strain (overall lengthening or shortening of an object) that you cannot detect it without sophisticated measurement techniques.

2. Ask students to compare the behavior of the marshmallow and the other objects at room temperature versus at 77 K.

   Discussion: In a similar way to the rubber bands, the marshmallow breaks in a brittle manner at 77 K. It retains neither its elasticity nor plasticity.

3. Ask students to think about the fact that real engineering materials, like steel at room temperature, might be analogous to the marshmallow at 77 K. Ask them to hypothesize how a steel would behave if its temperature were raised to 2000°F (roughly 70% of a typical steel's melting point).

   Discussion: As you might expect, the steel will become softer and easier to deform at higher temperatures. Steel that might otherwise break in a mostly brittle manner may break in a highly ductile manner at 70% of its melting temperature. Eventually, at a high enough temperature, the steel will sag under its own weight, similar to silly putty. As mentioned in the Background Information section, steel is one of the most commonly used materials for engineering applications. If it is too cold, it will be too brittle, and if it is too hot, it may be too ductile. The key is to strike the right balance.

Student Question Handout

Fun with Liquid Nitrogen

1. How does the rubber band behave at room temperature?

2. How does it behave after being subjected to liquid nitrogen?

3. What caused this behavior?

4. How does the marshmallow behave at room temperature?

5. How does it behave after being subjected to liquid nitrogen?

6. What happened to the ping pong ball after it was removed from the liquid nitrogen?

7. Why do you think this happened?

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