The "Atomic Trampoline" Kit:
Demonstrations with Amorphous Metal

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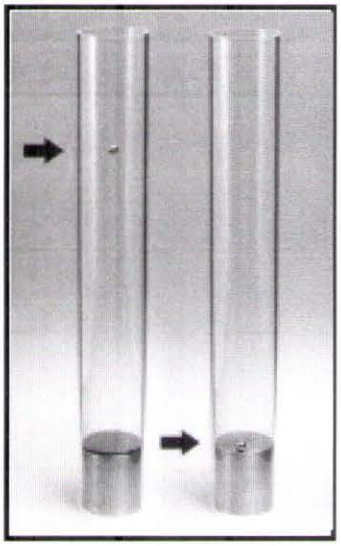

Figure 1. The amorphous metal demonstration.

This demonstration uses the following materials (Figure 1):

- one aluminum base
- one aluminum base with a 1/8" thick disk of Liquidmetal® ($Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10.0}Be_{22.5}$) glued atop it [1]
- two 12" tall clear plastic tubes
- two small stainless steel ball bearings

Warning: Liquidmetal® contains zirconium, copper, titanium, nickel and beryllium. Several of these elements are highly toxic. Although the disks are perfectly safe and can be handled without special precautions, do not polish, sand, scratch, file, or chip the Liquidmetal® disk. This will ensure that particles of the alloy do not come in contact with skin and cannot be ingested.

The Demonstration

To perform the demonstration, drop one ball bearing down the center of the tube with the aluminum base and watch how it bounces on the surface. Then, take the same ball and repeat the experiment using the base with the Liquidmetal® disk. Quite unexpectedly, the ball bearing bounces on the Liquidmetal® disk as if on a trampoline! A variation of the experiment is to drop two ball bearings simultaneously, one on each surface, for a direct comparison. Liquidmetal® is a metallic alloy with an amorphous structure, whose physical properties are quite different from those of crystalline materials.

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A National Science Foundation
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Rev. 11/05

The Explanation

The spectacular difference between the ball's interaction with the stainless steel and the amorphous metal surfaces is due to the different types of atoms and their arrangements on the two surfaces: as idealized in Figure 2, crystalline materials have an ordered repeating pattern of atoms (left), and the amorphous metal has five different kinds of atoms, each with a different size, leading to a highly disordered arrangement (right).

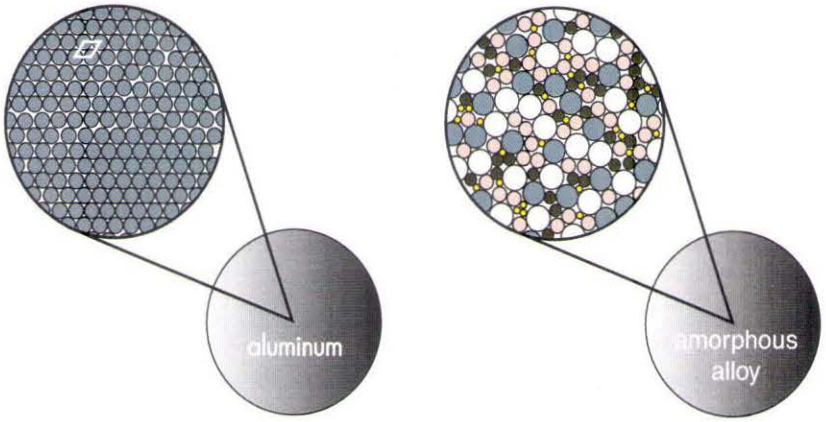

Figure 2. Idealized atomic view of aluminum (left) and Liquidmetal"™ (right).

The ball bearing bounces much higher and longer on the amorphous metal base than it does on aluminum, or almost any other crystalline material.

This demonstration highlights the interaction between the ball and the two metal plates. When the ball is dropped, it possesses kinetic energy. Some of the ball's kinetic energy will be converted to heat as it collides with either surface. Each collision causes movement of atoms in both the ball and the plate, and this motion is a kind of atomic friction that produces heat. In a perfectly elastic collision no kinetic energy would be lost, and the ball would bounce to its original height. Such a collision is not physically possible. In fact, whether the ball is bouncing on the amorphous metal disk or on the aluminum surface, its kinetic energy is converted to other forms of energy through collisions with the plastic tube, friction with gas molecules in the tube, and the generation of sound. However, in comparing the two plates it is evident that there must be something very different about the two materials themselves to account for the difference in "the way the ball bounces." As will be explained in more detail below, the difference arises in large measure from the inability of the atoms of the amorphous metal to slide past each other as they move during the ball-plate collision. Relatively little of the ball's kinetic energy is converted to heat, leading to a more trampoline-like bounce.

To appreciate the remarkable mechanical properties of Liquidmetal®, compare them with those of crystalline materials like aluminum. A crystalline solid has a regular structure in which the atoms or molecules are arranged in a repeating pattern. The entire structure of a crystalline solid can be described by a small repeat unit called a "unit cell", as shown in Figure 3. Most metals, including aluminum, have crystalline structures. The unit cell of copper metal is shown in Figure 4 where each ball represents an atom of copper.

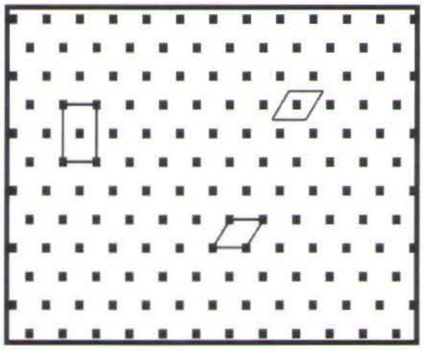

Figure 3. A hexagonal array of dots with several possible repeat units highlighted.

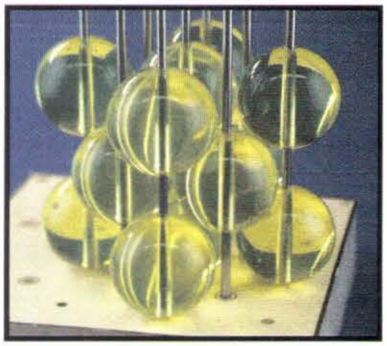

Figure 4. A unit cell of copper, built with the ICE Solid State Model Kit. [4] Each ball represents a copper atom.

The regular structure of crystalline solids is typically interrupted by defects. Examples of defects include impurities, missing atoms (a type of defect called a vacancy), and misaligned planes of atoms (another type of defect called a dislocation). Defects play an important role in determining the properties of a material. For example, even when the atoms in a solid are densely packed, the solid can be deformed due to the mobility of the defects and dislocations in the crystal. For example, copper wire bends easily because the dislocations are mobile, and facilitate the slipping or sliding of groups of atoms past each other, Figure 5. In this picture, the yellow circles represent copper atoms, and the curved line separates two rows of atoms (planes in three dimensions) that can slide past one another.

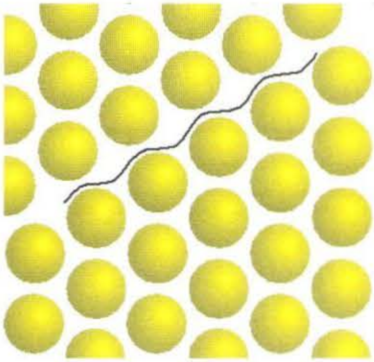

Figure 5. Copper atoms in a crystal. The curved line shows one direction along which rows of atoms can slide by one another.

There are many directions in which this can occur in a typical sample of copper. You may be able to see the effects of such energy-costly processes with the stainless steel plate: look for pits like those shown in Figures 6 and 7 as evidence of atomic motion.

Figure 6. Pits are evidence of atomic motion in the aluminum base after numerous ball-plate collisions.

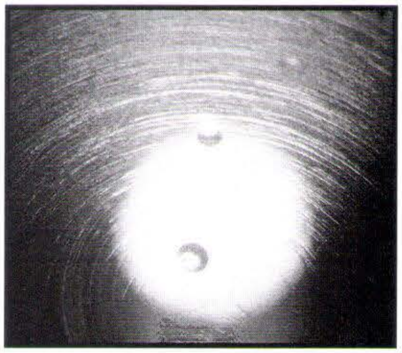

Figure 7. Several pits in the aluminum base are shown magnified 7.5 times.

The presence of impurity atoms within a solid can make the material harder, by creating "atomic gridlock". An impurity atom that is larger than the atoms in the solid acts like an "atomic speed bump," as the groups of atoms try to slide past one another; a smaller impurity atom acts like an "atomic pothole," again slowing the motion of the atoms through the solid, Figures 8 and 9.

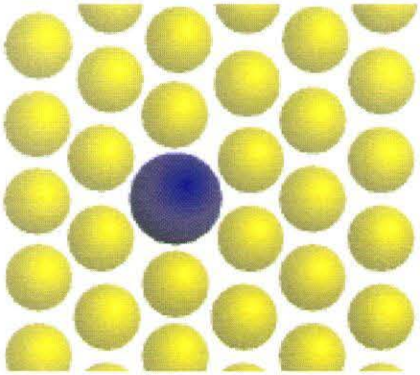

Figure 8. An "atomic speed bump", where a larger atom distorts the surrounding crystal, and makes the motion of atoms more difficult.

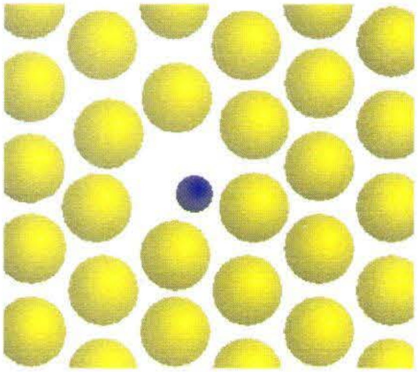

Figure 9. An "atomic pothole", where a smaller atom distorts the surrounding crystal, and makes the motion of atoms more difficult.

In striking contrast, an amorphous (noncrystalline) solid does not have a regular, periodic structure. The atoms in the amorphous alloy Liquidmetal® are in a densely packed, but random arrangement. Amorphous materials are formed by cooling the liquid material quickly enough to prevent crystallization; the atoms do not have time to arrange themselves into an ordered structure.

Liquidmetal® is an amorphous alloy (also known as a metallic glass) containing five elements. Its elemental composition is 41.2% zirconium, 22.5% beryllium, 13.8% titanium, 12.5% copper, and 10.0% nickel by relative numbers of atoms. Because of the varying sizes of these atoms (Figure 10) and their random arrangement in the solid, there are no groups of atoms that can easily move past one another. A consequence of this low atomic mobility is a "low internal friction" that minimizes the conversion of the dropped ball's kinetic energy to heat.

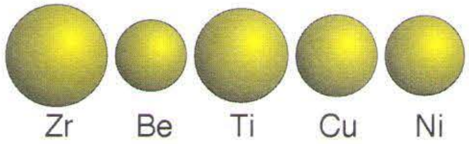

Figure 10. Relative close-packed metallic radii of the elements in Liquidmetal®.

Applications of Amorphous Metals

Liquidmetal®, discovered at the California Institute of Technology by W.L. Johnson in 1993, can be cooled from the liquid state at rates as low as 1°C/s and still form a completely amorphous solid [2]. This slow cooling rate is very unusual for amorphous metal systems that often need to be cooled at far faster rates. Consequently, it can be cast into molds and processed using various conventional metallurgical techniques. The unique properties of amorphous solids make them useful in many commercial applications. One of the first applications of Liquidmetal® has been in the design of golf clubs. It is generally accepted that a very strong material will transfer more of the impact energy from a golf swing to the golf ball. The Liquidmetal® alloy is two to three times stronger than many other conventional golf club materials like titanium and steel. Thus, a golf ball could be driven farther by a golf club head containing Liquidmetal®.

What would happen if the demonstration were performed with a golf ball? We encourage you to try this, but you may be disappointed with the results. Dropping a golf ball down a tall plastic tube is a very poor simulation of the actual ball-club interaction. To simulate the speeds generated in a real golf club swing would require a tube several stories tall. You could also try dropping small plastic or rubber balls onto each surface. It may surprise you that there is very little difference between the bounce behavior of the plastic balls on the two metal surfaces. This is because more of the ball-plate collision energy is associated with deforming the plastic ball.

Additional Information

Coefficient of Restitution: "rebound characteristics"

The coefficient of restitution (or the coefficient of elasticity) represents the degree to which an impact is elastic. A perfectly elastic impact, in which the kinetic energy loss is zero, would have a coefficient of restitution of exactly unity. Upon collision, one or both of the objects may deform, but their shape is restored in the elastic rebound. A perfectly inelastic impact, in which there is no rebound, has a coefficient of restitution of zero, and one or both of the objects are permanently deformed.

In this demonstration with bouncing spheres, the coefficient of restitution (e) can be determined using the equation below, by measuring the height from which the ball is dropped (h_1) and the height of the first bounce (h_2).

$$e = (h_2 / h_1)^{1/2}$$

Give it a try and see if you can estimate Liquidmetal's® coefficient of restitution.

Thermal Conductivity

Amorphous metals have other intriguing properties that are also a consequence of their structure and composition. Liquidmetal® has a lower thermal conductivity than many crystalline metals. In an experiment to test this, a small droplet of wax was placed on the top edge of each of four disks: Liquidmetal®, copper, stainless steel, and acrylic plastic (2" diameter, 0.125" thick). The lower half of each of these disks was dipped into a hot water bath at 90°C. The time it took for the drops of wax to melt down the faces of the disks was then measured. Copper has a thermal conductivity roughly 10 times higher than that of stainless steel [3]. As expected, the drop of wax melted very quickly on the copper disk (~10 s), and then on the aluminum disk (~ 75 s). The drop of wax on the Liquidmetal® disk melted next (~100 s), and the drop of wax on the acrylic disk had still not melted after more than 5 minutes. Touch the Liquidmetal® disk and then the stainless steel disk. Because of their differences in thermal conductivity (as evidenced by the ability of the metal to carry heat away from your hand), you may be able to detect a difference in how cool the two surfaces feel. Try touching other metal surfaces, too, and see if they feel cooler than the amorphous metal.

Important Note about the Liquidmetal® Disks

The Liquidmetal® disks are glued to the aluminum bases with a type of adhesive called Loctite 404. If the disk becomes partially or fully unglued (this can occur if the demonstration is dropped or subjected to extreme temperature changes), you will notice that the disk develops a "dead" spot. You can identify a "dead" spot by listening for a distinct change in the sound of the bouncing ball, as well as seeing the ball stop bouncing suddenly when it hits this spot. If you identify a "dead" spot, you will need to remove the disk and reattach it to the base. To cleave the disk from the base, turn the base on its side, and strike the edge of the disk gently with a hammer. **Warning: Liquidmetal® contains zirconium, copper, titanium, nickel and beryllium. Several of these elements are highly toxic. Do not do anything to the disk that might generate dust particles, such as cutting, grinding, filing, or polishing.** Then clean the two surfaces and reapply some instant glue, quick-set epoxy or other adhesive to reattach the disk. Make sure that as the adhesive dries the disk remains exactly centered on the base so the clear plastic tube will slide easily over the disk and base. As the glue is drying, gently drop the ball bearing onto the disk from several inches above it and listen to the pitch of the bouncing to make sure there are no "dead" spots.

Notes for Teachers

The following are some ideas for incorporating this demonstration into your classroom and laboratory.

1. This demonstration can be used as a discovery experiment for a small or large group of students. For example, provide students with some skeletal information about the two materials and their structures, and ask the students to propose possible explanations for the different physical properties. Encourage them to "test" the rebound characteristics of other materials around the classroom (i.e., wood, plastic, cement, or other metals) by placing the plastic tube over the material and watching the ball bounce. Based on their knowledge of the structures of these other materials, they may amend or extend their proposed explanation.
2. Ask students to measure the coefficient of restitution for the Liquidmetal® alloy and the aluminum, as well as other materials in the classroom using the aluminum (or other) balls. If a video camera is available, students can videotape the demonstration with a meter stick held in place next to the plastic tube. This will allow them to review the tape and make more careful height measurements.
3. A video clip of this demo is available on the website *http://www.mrsec.wisc.edu/edetc/amorphous*.

Acknowledgments

The authors would like to thank Bruce Clemens of Stanford University, Michael Ward of the University of Minnesota, Wendy Crone, Rod Lakes, Terry Millar, John Perepezko, and Donald Stone of the University of Wisconsin—Madison, for many helpful comments and discussions. We appreciate the design and fabrication assistance of Rick Pfeiffer, Kendall Schneider and Jerry Stamn. We are grateful for the Liquidmetal® samples provided by Howmet Corporation and Mark Degler. We acknowledge Mike Tenhover and Liquidmetal Golf for sending us information and a prototype demonstration. We are grateful to the National Science Foundation through the Materials Research Science and Engineering Center (MRSEC) for Nanostructured Materials and Interfaces (DMR-9632527) for support in developing this kit.

References

http://www.mrsec.wisc.edu/edetc/amorphous

This website has additional information, including updates on the kit and links to other useful websites. We invite you to contribute your reactions and ideas to the site by contacting the authors at ellis@chem.wisc.edu.

www.liquidmetaltechnoligies.com

This website has information on additional applications of this alloy.

[1] The Liquidmetal® disks were supplied by the Howmet Corporation.

[2] A. Peker and W.L. Johnson, *Appl. Phys. Lett.* **63**, 2342 (1993).

W.L. Johnson, *Curr. Opin. Solid State Mat. Sci.* **1**, 383 (1996).

W.L. Johnson, *Mater. Sci. Forum* **225-227**, 35 (1996).

[3] *CRC Handbook of Physics and Chemistry*, 73rd Edition, Ed. D.R. Lide, CRC Press, Boca Raton, 1992-1993.

[4] The Solid State Model Kit is available from the Institute for Chemical Education, 1101 University Avenue, Madison, WI; 608/262-3033. *http://ice.chem.wisc.edu*