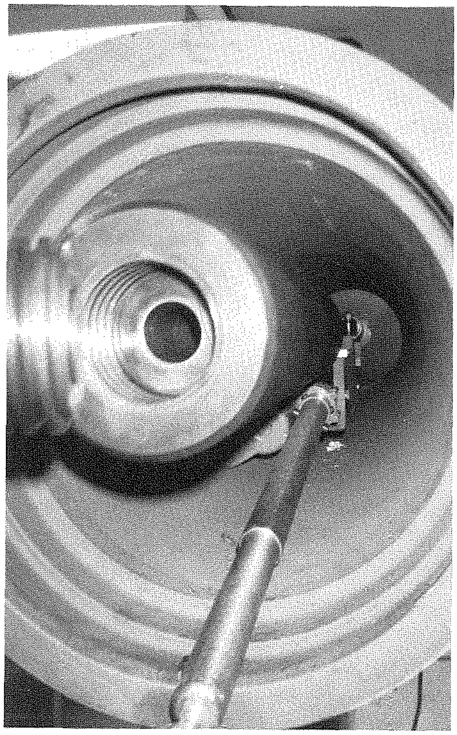
The Glass Menagerie

The cannon's breech. The cannon itself is sheathed in a 16-inch-diameter cast-iron pipe as a safety precaution.

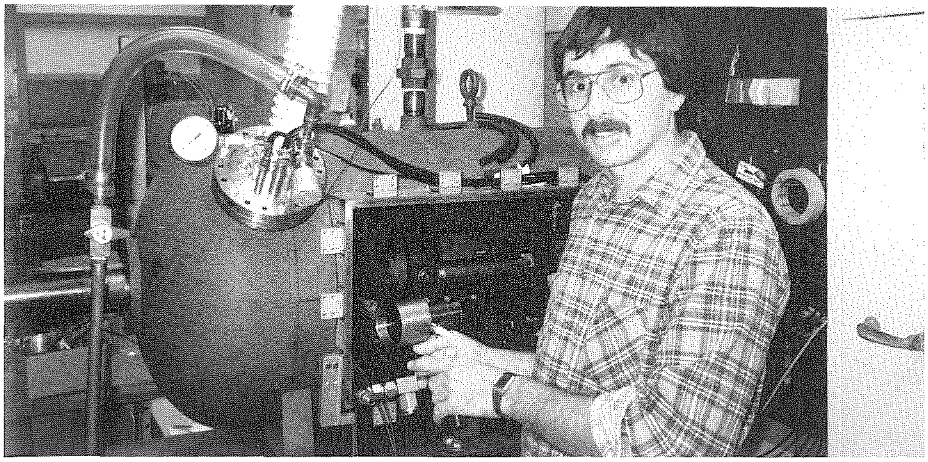


A "metallic glass" isn't a tin cup. A tin cup, like every ordinary hunk of metal, is crystalline—its atoms packed in a neat, orderly arrangement that repeats itself over and over throughout the material. A glass, however, is amorphous—its atoms are all jumbled together higgledy-piggledy, with no repeating order. A metallic glass is composed of metallic atoms, such as nickel, that have forsaken crystallinity for amorphism.

Metallic glasses have several useful properties. They are very strong under tension; a metal fails when stretched because dislocations (tiny crystal defects—missing atoms or planes of misaligned atoms) migrate through the crystal until they link up to become fractures. But an amorphous material has no set structure, so either dislocations don't form easily, or they don't travel well—the reason isn't clear yet, but metallic glasses will pull enormous loads. Metallic glasses also have superior magnetic properties. A magnetizable crystal—a chunk of iron, for example—consists of magnetic "domains," within which every atom has the same magnetic orientation. Each domain normally pairs with an equal-sized domain of opposite polarity, and their magnetic fields cancel. Apply an external magnetic field, and the domains aligned with it grow at their partners' expense. But any one atom can't easily realign itself because its reactionary neighbors—the other atoms in the domain, whose magnetic moments are bound in lockstep along the crystal axes—wield great influence. Thus a strong field must be applied before magnetic *perestroika* can occur. In the anything-goes disorder of an amorphous material, however, atoms can easily align themselves with a weak or fast-changing field. Thus metallic glasses would make ideal electric motor and transformer cores, and, on a smaller scale, Sony is already making tape decks with metallic-glass heads.

The trick to making metallic glass is to cool molten metal so rapidly—about 1 million degrees per second—that the atoms don't have time to crystallize. Ribbons averaging 40 microns (millionths of a meter) thick have been commercially available since 1973, manufactured by squirting liquid metal onto a spinning copper wheel, but it's been very difficult to make anything thicker.

Until now. Joseph Bach, now a junior in aeronautical engineering, took up the problem on his Summer Undergraduate Research Fellowship (SURF) last summer with Brent Fultz, assistant professor of materials science, and graduate student Barry Krueger. "There are a lot of things about bulk metallic glasses that aren't well known," says Fultz. "We wanted to study compression behavior, for example. Well, you can't compress something that's 40 microns thick and four feet long." So they devised a scheme to make thick samples using the Keck Dynamic Compactor—a 35-millimeter howitzer donated to Caltech by Aerojet Ordnance and adapted to its new life in the Keck



Bach at the cannon's business end. The target receptacle, which can be seen inside the safety enclosure, is mounted on shock absorbers. (The enclosure also serves to contain the gunsmoke.) The fitting he's holding screws onto the cannon's muzzle, and contains the fiber-optic and radar feeds as well as the vacuum connection.

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Laboratory by Thad Vreeland, professor of materials science, and graduate student Andy Mutz. It now resides on the third floor, where it is shared by several research projects, Vreeland's general studies of powder-consolidation mechanics among them.

Bach and Fultz figured that a projectile with just the right velocity would, upon slamming into a powdered metallic glass, generate a shock wave that could fuse the powder grains into a solid mass without altering their internal structure. Too little oomph wouldn't stick the grains together; too much would shove the atoms into a crystalline array. "The trick is to melt just a thin layer of the grains' surface so they'll stick together," says Bach. Adds Fultz, "We had reason to believe shock-wave consolidation would work, because it's a very rapid heating and cooling process. If you heat a metallic glass, it crystallizes before it melts. But others have found that if you increase the heating rate, you raise the crystallization temperature, so it doesn't crystallize quite so easily. You also lower its viscosity, so it flows a little bit better. So we were shooting for that window where the crystallization temperature is high enough to keep the material amorphous, but at the same time it flows and consolidates well, with no unfilled cracks."

Each shot followed the same general procedure. Bach ground store-bought glass ribbon (nickel-chrome alloy with a dash of boron to enhance glassiness) into a fine powder, and sifted it to get uniform-sized grains. Then he checked it by x-ray diffraction to be sure the heat of grinding hadn't crystallized it, and tamped it down into the sample container with a hydraulic press, using up to 30,000 pounds of pressure. Says Bach, "We tried to pack the particles as tightly as possible. We wanted to use as little energy as possible overall, so the less energy used to push the grains together, the better. And we didn't want the powder flying all through the gun when we turned on the vacuum." The sample container, an inch-thick hardened stainless steel ring, was sealed to the gun's muzzle, and the gun barrel evacuated to remove air resistance to the projectile, or "flyer plate"—a flat cylinder that slid down the barrel face first, like a quarter into a coin wrapper.

The upshot of each firing was a disk about the size of an Oreo cookie and half as thick; plenty thick for a compression test, and with material to spare for hardness tests, x-ray diffraction studies, and microphotography.

The group reduced the propellant charge with each shot to find the minimum workable flyer-plate velocity. Two independent systems measured the impact velocity—a Doppler radar like the one that bags speeders, and a fiber-optic system that shot two beams of light across the flyer's path and measured the time difference between the flyer's interruption of each beam.

The first shot had too much punch. The sample wound up half amorphous and half crystalline. It would have crystallized completely, but for the fact that the flyer hitting the powder produces two shock waves. One travels forward into the powder, compacting and fusing it. The other propagates backward into the flyer plate, bounces off its rear wall, and heads forward again. The wave's character changes upon reflection, becoming a "release wave" that pulls the material apart rather than compacting it.

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The release wave enters the now-consolidated powder about a microsecond after the shock wave. Because waves travel faster through denser material, the release wave rapidly overtook the shock wave and partially canceled it, leaving the powder beyond amorphous. "We learned a lot from that first shot," says Bach. "The crystalline and amorphous zones were perfectly flat and parallel, so we knew that the shock was planar and propagating very evenly through the powder. Then for the next shot, we doubled the plate's thickness to nine millimeters so that it would take longer for the release wave to reach the powder. We also reduced the propellant charge to lower the flyer velocity."

The second shot crystallized all the way through. The flyer plate was still going too fast and giving the shock wave too much energy, but at least the release-wave problem had been solved. So they cut back on the powder again.

The third shot was a bang-up success, as were three more. The x-ray diffraction and hardness tests showed that the material was amorphous, and photomicrography didn't reveal any cracks or voids. The compression tests are under way.

"These are not the largest samples ever made, but they are certainly the easiest to make," says Fultz. "A Japanese group is fusing ribbons by heating them and running them through a rolling mill very quickly. But you have to be very nimble with your torches. It's a big nuisance to set up and very tricky to make work. We just load and fire, and the process is very controllable—you can predict what you're going to get. It's been a big success for a small SURF project."□—*DS*

Top: Metallic glass samples. The cube in the middle is ready for compression tests. Bottom left: Cross section of the first sample, magnified 50×. The sample is amorphous on the left side, crystalline on the right. Bottom right: Close-up of the transition zone, magnified 400×.