

# TOUGH STUFF

## **EXTREME MATERIALS** for **EXTREME CHALLENGES**

If you're going to make bombs, and you want them to perform predictably and reliably, then you want to know how the materials they are made of behave under extreme conditions. Metals such as steel or aluminum or plutonium are not uniform throughout: they have microstructure—various ways the metal grains are connected at the microscopic level. And it is the microstructure that determines their behavior—how they deform in an explosion or an automobile collision, how they fail at high temperatures. The microstructure, in turn, is influenced both by the composition of the material, by how it is processed or formed into useful parts, and by how the material ages.

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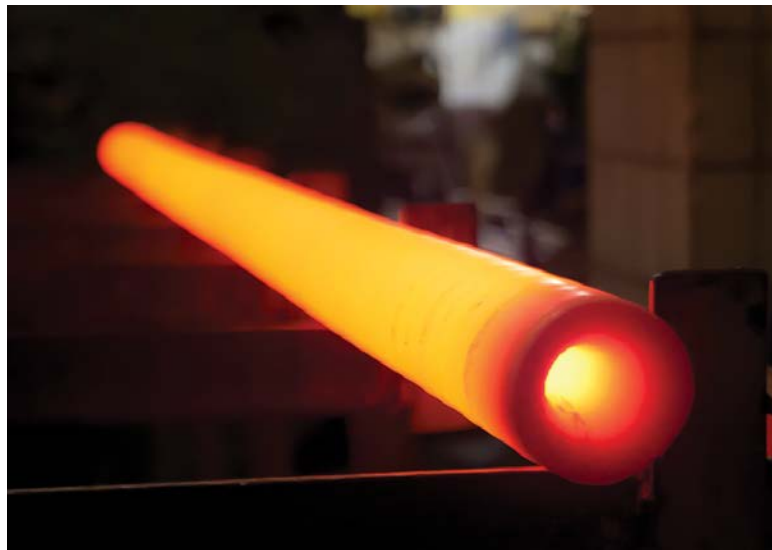
An unarmed B61-12 gravity bomb, part of the U.S. nuclear weapons stockpile, undergoing tests. *(Sandia National Laboratories)*

Very little was known about such questions when the Basic Energy Sciences (BES) program of DOE was created in 1977. Responding to a clear national security need to better understand how materials deform—for both nuclear weapons and conventional bombs—BES initiated what turned out to be four decades of fundamental research into the microstructure of materials. National security was not the only challenge: coal-fired power plants and steam boilers also push materials to their limits, and both could operate at higher efficiencies if their materials could withstand higher temperatures. Nuclear power plants put materials under intense radiation that can damage them and potentially shorten the useful lifetimes of these expensive facilities.

The BES research program studied many different metals and metal alloys. With the specialized tools at BES shared research facilities, the materials were probed with intense X-rays to map the microstructures; analyzed with neutrons to measure the microstructure alignment and the exact positions of atoms even deep inside the metal; imaged with electron microscopes; and studied with some additional, novel methods developed in the course of the research. Individual investigators at universities and scientists at DOE national laboratories played major roles.

What has emerged is a whole new science capable of predicting how materials deform, how they age, how they fail, and how to make them stronger. Materials scientists have developed new alloys now used commercially around the world and new metal processing techniques that remove defects and problematic microstructures. The impact of this new “tough stuff” science includes:

- > A computer program, or code, that can simulate material behavior—the so-called visco-plastic deformation code—which is routinely used both for national security purposes and throughout the U.S. manufacturing industry. Bomb makers and car makers use the same code to test how new weapon designs will work and how a new lightweight bumper on a Chevy truck will perform in a crash.
- > A second type of code can simulate how processing materials by such techniques as casting or cold rolling or machining could affect their microstructure and hence their behavior. For example, cold rolling of steel plate, if done in a certain way, produces more uniform steel



Top: Hot metal cooling after casting. (*Tdhster / Shutterstock.com*)

Bottom: Rolling mill processing steel plate. How metals are processed affects their microstructure and hence their properties. (*Sayam Tirattanapaiboon / Shutterstock.com*)

with much-reduced defects, so that it is stronger. That means less steel is needed—a thinner piece will do. The code applies to many different metals and alloys and has found very widespread use in steel plants and other metal-forming facilities. It has had a major economic impact on industry, enabling the widespread use of lighter but stronger materials in cars, airplanes, and many other applications, such as the new Ford F-150 pickup that uses aluminum, not steel, for the body.

- > Steel is no longer just steel. As a result of the growing knowledge about how the composition of steel affects its microstructure and hence its properties, steel and other metals are now “tuned” for specific applications. For example, chrome-molybdenum steel is a super-strong alloy developed from BES research and used worldwide in coal-fired power plants, in pressure vessels, and in other energy production processes for its ability to withstand higher operating temperatures, which increase power plant efficiency. Chrome-molybdenum steel is also used in bicycles, cars, and airplanes.
- > Nuclear reactors were originally licensed for a 40-year lifetime, in part because of concerns about the embrittlement and stress cracking of the reactor vessel’s steel from nearly constant exposure to intense radiation. But greater understanding of the embrittlement and stress cracking process from the BES research effort has allowed regulatory authorities to extend nuclear power plant operating licenses to 60 years, with 80-year licenses under consideration. Some experts believe that a 100-year operating life will be possible for next-generation nuclear power plants, using improved steels.

A very unique materials problem that BES took on concerned plutonium, a key ingredient in nuclear weapons. Plutonium has a split personality—it comes in brittle and ductile forms, and if you try to machine a bomb part with brittle plutonium, it shatters. BES-supported research found that the cause of this duality stems not from plutonium’s microstructure, but from its chemical bonding. It turns out that plutonium’s electrons can form two kinds of bonds, one leading to the ductile form and one to the brittle form. Once this subtle phenomenon was understood,



Ford F-150 trucks now use high-strength aluminum rather than steel for their body, reducing weight and increasing efficiency and pulling power. (*Drifting Light / Shutterstock.com*)

researchers found ways to nudge plutonium into a reliably ductile form by alloying it with a small amount of the metal gallium—making life much easier for the nation’s nuclear warhead-makers.

As the U.S. sets out to upgrade its infrastructure—from bridges and ports to power plants and the towers that carry the electric power grid—the ability to design and manufacture materials that are stronger, lighter, and better able to resist corrosion will repay the ongoing investment in materials research many times over.

The nation’s nuclear stockpile is also aging—currently-deployed weapons are well past their intended lifetimes, raising questions about aging phenomena and associated radiation damage. Updating the weapons stockpile will also require new manufacturing practices, because changes in technology and regulations mean that weapons materials cannot be made the same way as in the past, which might affect how they perform. The new Nuclear Posture Review also envisions a deterrent that is more agile and flexible. All of these considerations mean that the fundamental science base enabled by BES will likely be called upon to address important and emerging national security questions.