

## Fighting Friction

When you're sitting in a chilly room and your hands feel cold, rubbing them together can be the quickest way to warm them. To engineers, this natural heat source is known as friction. And while it may be good for our bodies, it is also a mechanical nuisance that has cost the U.S. billions of dollars in lost labor, down-time and cost of replacement parts.

It's mechanical challenges like friction that have sparked the development of a field known as tribology — a branch of engineering devoted to studies of friction, wear and lubrication. Recently, joint effort between tribologists at Argonne and materials scientists at the University of Illinois at Chicago and Drexel University has resulted in the development of a carbon-based coating that can reduce mechanical friction by up to 75 percent. This coating, known as Nanostructured Carbide Derived Carbon (CDC), was named one of the top 100 inventions last year by R&D magazine.

Key to the coating's success is the presence of carbon nanostructures — tiny particles spanning no more than a few nanometers across (a nanometer is a billionth of a meter). According to Argonne scientist Ali Erdemir, who collaborated in developing the technology, these nanostructures come in at least five different forms, ranging from flat sheets of graphite to cylindrical structures known as "nanotubes.

"There are many coatings on the market that are based on only one phase of carbon, such as graphite or diamond, explained Erdemir. "However, the nanostructures we found in CDC coating represent almost all of the major chemical phases of carbon. This combination makes our coating unique.

Laboratory tests show that CDC is more wear-resistant than coatings made from single-phase graphite or glassy carbon. However, the main benefit of CDC technology is its versatility. Since each phase of carbon has different characteristics, scientists will eventually be able to apply the technology to a wide variety of materials simply by adjusting the ratios of nanostructures within the coating.

Friction, a force that occurs when two surfaces rub against each other, has been one of mankind's worst enemies when it comes to creating long-lasting, efficient machines. Even with two objects that look smooth, microscopic rough edges can be found along their surfaces that generate resistance when they slide against one another. In macroscopic terms, this resistance translates into material wear and tear and wasted energy in the form of heat.

"It is estimated that anywhere from one-third to one-half of the world's energy production is used to combat friction and wear, said Erdemir, commenting on the importance of energy efficiency. "Therefore, even very small improvements in efficiency and durability within mechanical systems can save billions of dollars.

For these improvements to happen, however, scientists have to find ways to decrease resistance between mechanical surfaces. The solution to this problem, making the surfaces smoother, may seem simple. Yet, tribologists are still looking for slicker and more durable coatings that will make surfaces as close to friction free as possible.

## **Carbon: the secret weapon**

Following on the heels of household substances such as WD-40 and Teflon, carbon-based coatings seem to be the next step in the search for the ideal lubricant. As the sixth most common element on earth, carbon is known for its ability to bond in many different ways. This ability allows carbon to be used for high-friction applications, such as aircraft brakes, as well as low-friction coatings.

Erdemir, for his part, is well-versed in the many ways that carbon can help tribologists. In 1991, he began work on a Near Frictionless Carbon coating that later won a R&D 100 award. The success of this near frictionless coating, which also had the highest wear resistance of any solid material, inspired Erdemir to conduct further investigation into other ways to synthesize carbon lubricants.

"My main interest was in finding ways to synthesize diamond — a form of carbon that's known for its excellent lubrication properties. If we could find ways to synthesize diamond films at atmospheric pressure, it would be a very economical way to protect machines against the effects of friction, said Erdemir.

While searching for synthesis methods, Erdemir came across a group of researchers from the University of Illinois at Chicago and the Drexel Nanotechnology Institute that had developed a way to make carbon films from metal carbide — a compound of carbon with one or more metallic elements. Their film, which was made by taking metal carbide and exposing it to high-temperature chlorine gas at atmospheric pressure, appealed to Erdemir because of its simplicity. He began to collaborate with the researchers in 1997, using his expertise to adapt the Carbide Derived Carbon for use as a low-friction coating.

## **Carbide Derived Carbon: A harmony of nanostructures**

Closer examination of the CDC film revealed just what Erdemir was looking for: a thin layer of diamond nanocrystals. The presence of that layer marked the first time anyone had ever synthesized diamond at atmospheric pressure. However, his discovery also came amid a treasure trove of nanostructures that no one expected to find.

"It's amazing. The film is like a graveyard for all different kinds of carbon structures, Erdemir recalled.

The CDC coating turned out to be composed of approximately five or six different layers, each of which is dominated by the presence of a particular nanostructure. Graphite, diamond, polyhedral nanotubes and "nano-onions — small carbon spheres with concentric rings — are just some of the structures unearthed by Erdemir and his team.

These layers exhibit different characteristics of lubrication and vary between two and ten nanometers in thickness.

"Having these layers of nanostructures co-existing with each other is crucial for the success of CDC coating, said Erdemir. "Not only does their overall effect allow for the coating to be an excellent lubricant, but it also allows us to 'tune' or adjust the coating for use in many different applications.

Erdemir expects this flexibility to be one of the main advantages of CDC coating. Indeed, just increasing the width of the nano-onion layer would allow the coating to be used for hydrogen storage, while increasing the width of the graphite and diamond layers would allow it to be used on gears and other mechanical sliding devices.

After examining the chemistry of the coating, Erdemir turned to his Argonne-based team of researchers to find out the coating's properties in regard to friction and wear. Using tools such as heavy steel balls and gas chambers, the researchers constructed a variety of "torture tests that would expose the CDC film to harsh environments similar to those found in real-world scenarios.

Stress tests on mechanical seals offered conclusive proof of CDC's usefulness. For example, water seals that were treated with the special coating lasted over seven times longer in a dry-run test than those that were untreated.

Erdemir and his collaborators are now working toward transferring the CDC technology to industry — a project that should be straightforward, given the relative ease with which scientists were able to make the coating. In the meantime, he continues to envision many applications for the coating such as filters and adsorbents for biohazardous agents or for use in prolonging the life of automotive engines.

"It's the harmony of the nanostructures within CDC that makes it so versatile. We are still working to understand the material at the nanoscale level, but an understanding of the nanoscience behind CDC coating would definitely shed light on more efficient ways to reduce friction and save energy in mechanical systems, said Erdemir.

### **Argonne scientists unite against friction**

Erdemir's role in creating CDC technology is just one example of Argonne's long legacy of success in tribology. With a wide variety of research efforts being supported by the Department of Energy's Office of Transportation Technologies and by U.S. industry, the tribology division focuses on developing coatings and technologies to protect engine-component surfaces in advanced transportation and energy conversion systems.

In addition to the work of Erdemir and the Energy Technology Division at Argonne, other collaborators on the CDC coating project include Michael J. MacNallan, professor at the University of Illinois at Chicago; Bart Prorok, professor at Auburn University;

Yury Gogotsi, director of the A.J. Drexel Nanotechnology Institute; and Sascha Welz and Daniel Ersoy, both Ph.D. students at the University of Illinois at Chicago.

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