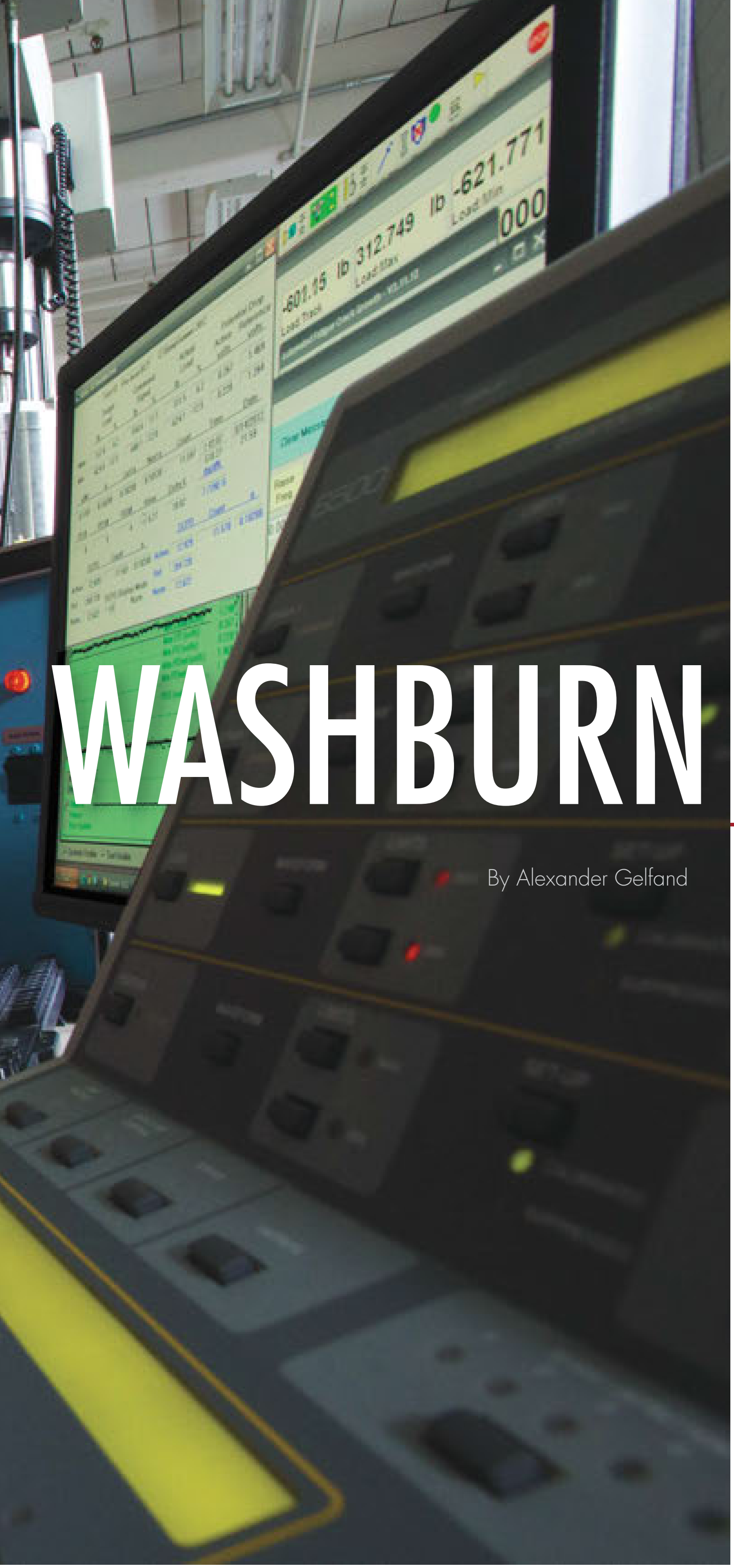
THE WIZARDS OF

Diana Lados, right, and postdoctoral student Anastasios Gavras prepare to run a sample through the rigors of mechanical testing in the Washburn Shops, home to WPI's materials science and engineering programs. Lados studies the properties of metals that make them prone to fatigue, which is the cause of most metal failure.



WASHBURN

By Alexander Gelfand

Richard Sisson Jr., George F. Fuller Professor of Mechanical Engineering, has a gift for boiling things down to their essence, and a sense of humor that comes through even when he's talking shop. His colleague Yan Wang, assistant professor of mechanical engineering and an expert on rechargeable energy cells, is "the battery guy." Diana Lados, associate professor of mechanical engineering and a specialist in metal fatigue and fracture mechanics, "breaks things."

VIDEO EXTRA
Professor Lados explains why metal parts fail.

But when Sisson claims that he and his fellow metallurgists have magical powers—"We're the wizards and warlocks," he says from his office in the Washburn Shops—one gets the distinct impression that he's only half joking.

Metallurgy, the science of creating, processing, and using metal alloys, has been a focus of education and research at WPI since the Institute opened its doors in 1868. Where students once gained hands-on experience working in a foundry and crafting products for sale in the Washburn Shops, faculty and student researchers today advance all aspects of the science and engineering of metals in an impressive array of laboratories in Washburn that fall under the umbrella of the Metal Processing Institute (see sidebar, page 14) and the Manufacturing and Materials Engineering programs, which Sisson directs.

Through this research, and through the application of advanced computational tools, they are taking the theory and practice of materials science and engineering to new places, and to new levels of sophistication. They are, as Sisson says, performing feats of metallurgical magic. Fortunately, they only use their powers for good.

Right, Richard Sisson and graduate student Danielle Belsito examine a metal sample under a light microscope. When viewed under the scanning electron microscope in Washburn, more of the sample's microstructure is revealed, as seen in this image of a cold-sprayed aluminum powder.

VIDEO EXTRA

Professor Sisson on the need for designer metals.

Super-Materials by Design

"Metallurgists heat things up and cool things down," Sisson says. "The key is how hot, how long, and how long you cool it in the end," adding that all of those factors affect the nanoscale microstructures inside the alloys, and thus their physical properties. Armed with a $4 million contract from the U.S. Army, Sisson and his colleagues are using computer models to predict the response of metal alloys to heat treatments, with the goal of developing computational tools that can be used to refine existing aluminum alloys and develop new ones that the service can use to build and repair its airplanes and ground vehicles.

The alloys the Army now uses are strong, but not particularly tough or ductile. Typically, they are first turned into powder and then sprayed at high temperatures. Everything from the initial composition of the powders, to the way they are heated, influences their performance. One of Sisson's goals, therefore, is to develop processing techniques that can enhance toughness and ductility without sacrificing strength.

Another is to invent new alloys strong enough to be used structurally, tough enough to function as armor, and light enough to improve the mobility and gas mileage of army vehicles such as Humvees. "They want super-materials," Sisson says. "They want them to have three or four functions at once."

That's a tall order. But Sisson has more than a few tricks up his sleeve. For example, the databases that he uses to power his computer models often lack crucial data on the physical properties of specific alloys. So Sisson is conducting physical experiments to fill in those lacunae, improving his ability to accurately simulate each step in the creation, treatment, and application of a given metal. Ultimately, that will help him design new and better materials—a task that depends on understanding exactly what properties are required, and which processes will produce the microstructures needed to generate them.

Sisson is also investigating a low-temperature method of applying the alloys, known as cold spraying, that accelerates the powders to supersonic speeds without actually melting them. Though well-suited to preparing vehicle parts at relatively low cost, the process is still in the experimental stages.

Sisson acknowledges that developing next-generation alloys using next-generation technologies is no small undertaking. But the wizard of Washburn is undeterred. "If it was easy," he says, "everyone would be doing it."

VIDEO EXTRA

Professor Wang on how to make a better flow battery.

Recharging Energy Storage

Yan Wang, director of the Electrochemical Energy Laboratory, is attempting to perform some magic of his own: by offering a novel spin on a type of rechargeable fuel cell called a flow battery, Wang hopes to help take wind and solar power mainstream.

In a conventional flow battery, electrolytes are stored in external tanks and pumped across a membrane in a central chamber to generate the chemical reactions that store or release electrical energy. Flow batteries don't need electrodes, which simplifies their design. Because they require less physical packaging material, they are more compact and cheaper to manufacture than ordinary batteries. And they are easy to scale since, as Wang explains, "the total energy is not limited by your battery size." Need more capacity? Just build bigger tanks.

That makes flow batteries the leading candidate for storing the energy generated by wind turbines and solar cells for use across an electrical grid when the sun isn't shining and the wind isn't blowing. But current flow battery designs have their limitations. For one thing, the metals used to make the electrolytes are not very soluble, resulting in low energy density. And while existing flow batteries store energy more cheaply than ordinary rechargeables (Wang says flow battery storage costs $300–$500 per kilowatt hour, compared with $1,000 per kilowatt hour for standard lithium-ion batteries), they aren't cheap enough to be commercially viable. The U.S. Department of Energy, for example, has set a goal of $100 per kilowatt hour for grid storage. Wang aims to meet that goal by doing away with conventional electrolyte solutions entirely. Instead, he wants to fill his flow batteries with thick suspensions of undissolved nickel and zinc particles. Because they are mostly metal, those dark, gooey suspensions (Wang has dubbed them "Worcester crude") possess 10 times the energy density of other electrolytes, and are much cheaper to produce. And because the suspensions

Yan Wang, center, and graduate student Qina Sa watch graduate student Zhangfeng Zheng prepare samples in the glove box in Wang's battery research lab. The team has developed a novel design for flow batteries, which are used for energy storage in power grids. The design uses thick suspensions of metal particles.

are based on water, they're safer than electrolyte solutions that rely on flammable organic solvents, like the ones that occasionally cause lithium-ion batteries to explode.

Wang and his students are building a prototype and working to improve the electrochemical performance of the suspensions. And while he has his eye on grid storage, Wang also envisions a day when cheap, clean, compact flow batteries might trickle down to other applications — like electric cars.

Imagine, for example, a vehicle whose fuel tank holds Worcester crude instead of gasoline. Never mind plugging into an outlet and waiting to recharge the battery once it runs down; thanks to Wang, a driver could simply pump out the depleted suspension and pump in a fresh load, "just like pumping gas."

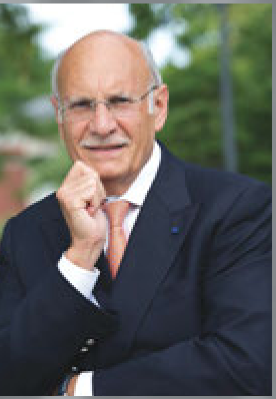
Bridging a Knowledge Gap

Like Wang, Diana Lados is interested in saving energy. But she comes at it from a very different angle. She recently received a five-year, $525,000 CAREER Award from the National Science Foundation to boost vehicle energy efficiency (and decrease greenhouse gas emissions) by replacing heavy structural materials like steel and cast iron with lighter metals such as aluminum, magnesium, and titanium. "Each 10 percent reduction in vehicle weight results in a 5 to 8 percent increase in fuel economy, and corresponding reductions in CO2 emissions," says Lados, who founded and directs WPI's Integrative Materials Design Center (iMdc).

Before those lighter materials can be widely adopted, however, engineers first need a better understanding of what causes them to fatigue, or break under repeated stress — a process that begins with microscopic cracks and ends with large fractures.

Replace, Reduce, Recover...Sustain

"Sustainable development is, perhaps, the most pressing issue of the 21st century," says Diran Apelian, Alcoa-Howmet Professor of Mechanical Engineering and director of the Metal Processing Institute. "At the same time, it is a remarkable opportunity for practitioners of materials science and engineering, as many of the approaches that can address the challenges we face are materials-centric."



Two years ago, WPI took a bold step toward elevating the role of materials research and education in sustainably. With a major award from the National Science Foundation, the university, in partnership with the Colorado School of Mines and Katholieke Universiteit Leuven in Belgium, established the Center for Resource Recovery and Recycling (CR^3).

Under the direction of Apelian, the center has set itself the goal of becoming "the premiere industry-university collaborative dedicated to the sustainable stewardship of our Earth's resources." Its focus is new technologies for maximizing the recovery and recycling of metals used in manufactured products and structures.

"This is a global issue," Apelian says. "It is significant that this is the first NSF-funded research center that includes a European university. In many ways, European nations are ahead of the United States when it comes to the recovery and reuse of materials. We have a lot to learn from their experience."

With its 38 members, including major materials producers, manufacturers, and leaders in recycling technology, CR^3's researchers are engaged in a wide range of projects, from developing ways to recover indium, rare earths, and ruthenium from plasma displays to pioneering real-time sensors for analyzing melts to boost the recovery of aluminum from scrap.

"The challenges of sustainable development are enormous," Apelian says. "It will take our collective ingenuity and collaboration across disciplines and national borders to achieve success. Through the CR^3, I believe we have established a model for collaborative, interdisciplinary research that can help point the way toward a more sustainable future."

Learn more: "Materials science and engineering's pivotal role in sustainable development for the 21st century," Diran Apelian, MRS Bulletin, April 2012; wpi.edu/academics/Research/CR3/2012pu035.html

Master's candidate Yuwei Zhai and Professor Lados inspect an aluminum sample undergoing a test in a machine that can stretch metal until it breaks. Knowledge gained by testing alloys can lead to better computational tools and greater use of light metals in cars, trucks, and airplanes.

According to Lados, 90 percent of all mechanical failures are caused by fatigue. Yet despite years of research, scientists still don't fully understand how those cracks form at the nano-level, especially in complex alloys. Nor have they managed to combine what they do know about small cracks with their understanding of large ones. That knowledge gap presents a problem, because without a clear picture of what's going on at every level, designers can't accurately predict how susceptible a particular metal will be to fatigue and failure under real operating conditions. So they build excessive weight into vehicle parts just to be safe.

Using a combination of computational modeling and hands-on experimentation, Lados and her students plan to explore how small cracks form in the microstructures of metal parts, how they propagate and grow into larger fissures, and how all of this ultimately leads to failure. To gather data and validate their models, Lados and her team will prepare different light metal alloys, process them using novel techniques, then break them and examine the corpses.

The iMdc, whose mission is to advance the state of the art and practice in sustainable materials, materials design, and manufacturing, will play a critical role in that process. Member companies, which represent all the transportation industries, along with manufacturing suppliers and metals producers, will use the alloys in real-world applications and help validate the tools and methods developed in the study.

What Lados learns about the relationship between small cracks and big ones, how cracks form and spread, and how a material's properties influence fatigue will help metal manufacturers develop new and better alloys. It will also help designers more accurately predict the lifespan of their components. And that, in turn, should lead to increased use of lighter metals in everything from cars to boats to planes.

That's all thanks to a little creative destruction—and a generous application of the real-world wizardry at work in every corner of the Washburn Shops, magic that is transforming the field of modern metallurgy. ■