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re:search

An inside look at innovation and discovery at Missouri University of Science and Technology // Fall 2014

Extreme engineering

S&T researchers are pushing ceramics to their limits to see what makes them stronger.

pg. 8

MISSOURI
S&T
University of
Science & Technology

Fiscal Year 2014 Summary

Proposals submitted

546

Dollars requested

\$155.9 M

Proposals awarded and amendments

307

Dollars awarded

\$ 30.7 M

Total expenditures

\$ 43.8 M

Faculty and staff serving as principal or co-principal investigators

227

Invention disclosures

45

Patent applications filed

29

Patents issued

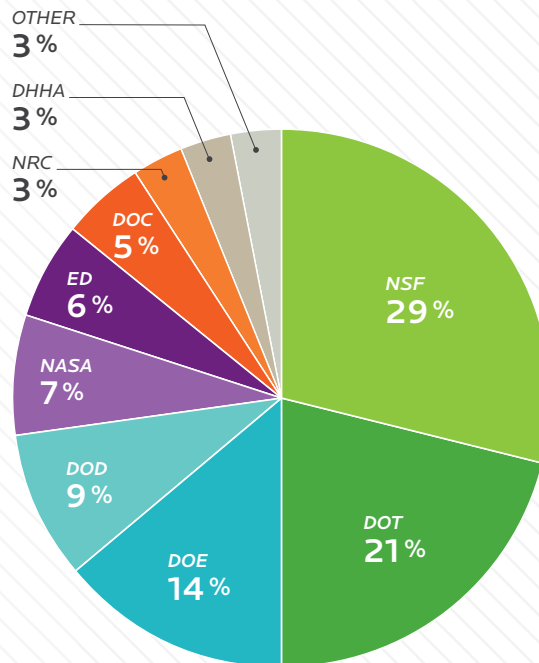
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Licenses/Options signed

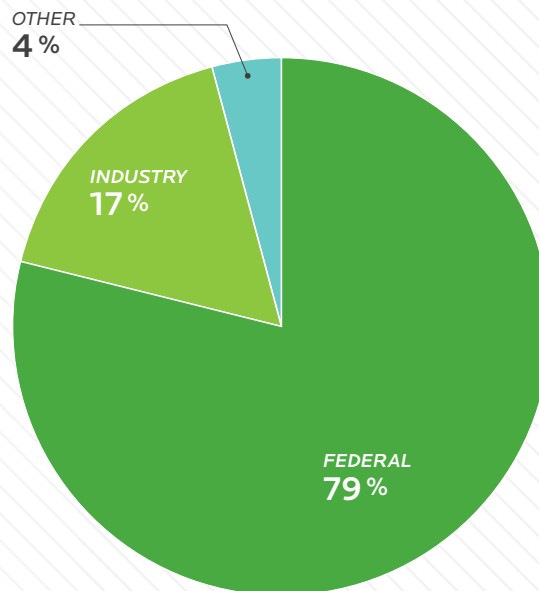
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Licensing income

\$ 368 K



FY14 federal awards by source (total amount: \$24.2 M)



FY14 total sponsored awards by source (total amount: \$30.7 M)



Dear Colleague,

This year brought significant change with the rollout of Missouri S&T's new strategic plan, *Rising to the Challenge 2013–2020*. I am particularly excited about our bold plan to hire 100 new faculty by 2020, our 150th anniversary.

A significant number of these faculty will be recruited in four signature areas — areas that build on Missouri S&T's distinctive research strengths to make them among the nation's best. Building on our continued success in these areas with strategic investment will embolden Missouri S&T to address nationally recognized grand challenges, including future national workforce needs.

The signature areas were chosen from proposals submitted by interdisciplinary teams of faculty who made compelling arguments for their plans to elevate Missouri S&T to best-in-class status. The four signature areas, listed below with the high-priority national needs they will address, are the focus of this issue of *re:search*.

Smart Living — sustainability and secure cyberspace

Advanced Manufacturing — additive manufacturing, micro- and nano-manufacturing and sensor-enabled intelligent manufacturing

Advanced Materials for a Sustainable Infrastructure — restoration and improvement of urban infrastructure in an environmentally sustainable manner

Enabling Materials for Extreme Environments — clean energy production, hypersonic flight vehicles and advanced propulsion systems

As we look forward, it is gratifying to note that past investments made in our early-career faculty continue to pay dividends. During this past year, four of our faculty members were honored with prestigious early career awards. Lian Duan received an Air Force Young Investigator Award, Jie Gao received an Oak Ridge Associated Universities' Ralph E. Powe Junior Faculty Enhancement Award, and Yiyu Shi and Zhaozheng Yin received NSF CAREER Awards. You can read more about their work on the back cover.

I hope you will take some time to learn more about the bold steps Missouri S&T is taking, as well as the impact our faculty and students are making through their innovative research.

Sincerely,

K. Krishnamurthy
Vice Provost for Research

On the cover

Missouri S&T researchers are investigating ultra-high temperature ceramics for a variety of aerospace applications such as thermal protection systems and propulsion components for hypersonic vehicles. Sharp leading edges, like the sample pictured on the cover, are a design requirement because they reduce drag on hypersonic vehicles traveling at extreme speeds under immense pressure and heat.

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re:search is the annual report on research, innovation and discovery activities at Missouri University of Science and Technology, formerly the University of Missouri-Rolla. Published by the Office of Sponsored Programs, *re:search* highlights only a portion of Missouri S&T's vibrant, focused research program. For more information about Missouri S&T's research, contact:

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Smart Living

Missouri S&T's Smart Living signature area provides technology that seamlessly transforms home, workplace, transportation and energy infrastructures into a "smart" environment to improve quality of life. Smart Living combines participatory sensing, social behavior analysis, data analytics, engineering and technology into one integrated concept.

A multidisciplinary team of faculty from Missouri S&T, led by **Sanjay Madria** and **Bruce McMillin**, both professors of computer science, and **Glenn Morrison**, professor of environmental engineering, are working to connect Missouri S&T's strengths in sustainable energy research, architectural design, environmental sustainability and transportation infrastructure through secure computing, sensing and network communications. These technologies are guided by behavioral and environmental psychology, sociology and infrastructure to develop a more secure, sustainable society.

In addition to the participation from Missouri S&T's two new colleges on campus, Smart Living will involve industry partners and University of Missouri System campuses to make the research a statewide effort. The Missouri S&T Solar Village will become a living environment for smart living and will eventually lead to citywide participation.





An example of a smart living environment is Missouri S&T's Solar Village (pictured here), where four solar-powered homes rely on a self-sufficient smart grid for power.

Building materials

"Buildings will be 'living labs' that allow researchers to gather feedback to improve infrastructure and chemical or biological environments," says Morrison. "Sensors can monitor energy usage, water usage or even broadband usage."

Smart grid

Fuel cells and batteries from automobiles help provide energy to the buildings connected to a smart grid. Automated sensors and intelligent systems in and among the buildings help to manage the use and flow of energy. For example, smart sensors in the house will shut off a home's A/C system when the residents leave for work and automatically restart upon their return. The impact, on a larger scale, could save thousands of dollars a year.

Transportation

Improved urban planning and infrastructure provide scheduled, individualized and cost-efficient transportation in "smart" living environments that will alleviate traffic, reduce emissions and cut down on fuel costs.

Disaster management

A "smart" city will provide timely information to the public regarding hazards and inform them of crisis situations. The city will also automatically report to first responders in case of any emergency.

Privacy

Data collection is anonymous and confidential. Residents' habits and preferences, incorporated into the feedback system, will lead to a sustainable home with little to no waste. "We don't want people to worry about their privacy," says Sanjay Madria, professor of computer science. "People must have confidence that the system will preserve their individual rights."

Security

Linking the systems in a smart household is vital because they monitor the usage of energy and ensure the accuracy of collected data. "Security development for a smart grid, privacy for data and anonymity in a system where it is inherent to collect data are a major focus for us," says Bruce McMillin, professor of computer science.

'Smart' = societal worldview

Worldview is a vital concept in any "smart" society. Technology can transform the behavior of people and their community, but that technology has to be responsive to the actual needs, wants and behaviors of society for it to be useful. For a smart system to thrive, it must also be sustainable. That means balancing the pace of technological change with social change and understanding the complex ways the two interact. It also means being careful stewards of finite environmental resources. "Smart Living proposes grounding the technological systems within societal worldview rather than solely using technology to drive society," McMillin explains.

Re-making America

Over the past decade, many of the world's top corporations and industries have called on Missouri S&T researchers to improve existing manufacturing processes and develop new processes and materials.

"We're always looking for ways to create new capabilities, improve performance and increase productivity," says **Ming Leu**, the Keith and Pat Bailey Missouri Distinguished Professor of Integrated Product Manufacturing at Missouri S&T.

Introducing advanced manufacturing processes is important to the nation's long-term, sustainable economic growth. U.S. manufacturing accounts for 12 percent of gross domestic product, 70 percent of private R&D spending and 86 percent of exports.

"To me, the hybrid aspect of traditional manufacturing and additive manufacturing is the future for the U.S. to remain competitive," says **Jagannathan Sarangapani**, the William A. Rutledge-Emerson Electric Co. Distinguished Professor in Electrical Engineering at Missouri S&T. "This aspect requires skill sets from researchers in a variety of disciplines."

One of S&T's four signature areas for teaching and research, Advanced Manufacturing has strengths in the emerging fields of additive manufacturing; energy manufacturing; micro- and nano-scale manufacturing; network-centric and cloud manufacturing; advanced materials for manufacturing; and intelligent, sensor-enabled manufacturing.

For example, S&T researchers are working to create "smart parts" by embedding sensors and

communication circuits that allow goods to be tracked throughout the supply chain.

"Recording the chain of custody from the point of manufacture of all of the product's components to the point the customer receives it is helpful when products are recalled," Sarangapani says. "It also can be used to help stop counterfeit, a rising problem worldwide."

In the advanced manufacturing area, S&T also has particular strengths in additive manufacturing, composites manufacturing and metal casting. In addition, its micro- and nano-manufacturing program has seen rapid growth in recent years.

"By building components one layer at a time using data from CAD models, additive manufacturing has the potential to fabricate 3-D components with novel material compositions with properties and functionalities that would otherwise be very difficult to create conventionally," Leu says. "In this area, S&T researchers have developed unique processes for making functionally gradient materials, a new concept for creating composites of continuously varying materials.

Missouri S&T's expertise in advanced manufacturing has been nationally recognized, which has opened up many collaborative opportunities. Most recently, S&T was one of 23 universities selected to join with industry, governmental agencies and other organizations to form the Digital Manufacturing and Design Innovation Institute, a new national innovative manufacturing institute based in Chicago. S&T is also a member of America Makes — National Additive Manufacturing Innovation Institute, an organization focused on helping the country grow capabilities and strength in 3-D printing.

"During the Henry Ford era, manufacturing was focused on mass production — just making enough quantity so the price could be reduced," Leu says. "Then came mass customization, where smaller quantities with more variety were offered. Now we're at the personalization era where parts are designed and fabricated for the individuals. The goal is to make a one-of-a-kind product at or near the same price as the mass production." ■



Finding connections

Suzanna Long, associate professor of engineering management and systems engineering, is working to ensure that the nation's supply network is efficiently and seamlessly connected — from raw materials to finished products. She says it's critical for the health and vitality of the U.S. and world economy.





Advancing manufacturing

By developing tailored materials and fabrication methods, S&T researchers are paving the way for a number of manufacturing processes. Here are a few examples:

- **Greg Hilmas**, Curators' Professor of ceramic engineering, and **Robert Landers**, professor of mechanical and aerospace engineering, demonstrated the additive manufacturing of a 3-D part by grading two ceramic materials, alumina and zirconia, which have different properties.
- **Umit Koylu**, professor of mechanical and aerospace engineering, is using selective laser sintering to create bipolar plates of different flow field designs for PEM fuel cells, a key issue for improving fuel cell performance.
- **K. Chandrashekhara**, Curators' Professor of mechanical and aerospace engineering, is using fused deposition modeling to manufacture sparse-build molds and dies to save material and cost for composites manufacturing and hydroforming.
- **Frank Liou**, professor of mechanical and aerospace engineering, and **Joe Newkirk**, associate professor of materials science and engineering, are working with Boeing and GKN Aerospace to repair worn components and to make components with gradients of two different metals.



Concrete, reimagined

D+. That's the barely passing cumulative grade the American Society of Civil Engineers gave U.S. infrastructure in its 2013 Report Card. A full national economic recovery will require serious infrastructure rehabilitation, and Missouri S&T researchers have come up with some innovative ways to accomplish it. And they're using environmentally sustainable approaches to do it.



Bridge of the future

From left, graduate student Alex Griffin and Ph.D. candidates Eli Hernandez and Hayder Alghazali work with professor John J. Myers, professor of civil, architectural and environmental engineering, on the design and construction of a new highway bridge outside of Jefferson City, Mo., that uses new longer-lasting concrete beams developed at Missouri S&T. Photo by Terry Barber.



Kamal H. Khayat, the Vernon and Maralee Jones Professor of Civil Engineering and director of Missouri S&T's Center for Infrastructure Engineering Studies, is leading a team of investigators in the Advanced Materials for Sustainable Infrastructure signature area. They're working to make high-performance environmentally friendly construction materials to improve the nation's deteriorating infrastructure.

Concrete typically includes four key components: Portland cement (the "glue" matrix after reaction with water), water, fine aggregate (sand) and coarse aggregate (crushed rock or gravel). But Missouri S&T researchers are adding new materials to the mixture, like recycled concrete, fly ash (the by-product of a coal plant), fibers, fillers like ground-up tires and glass, and chemical admixtures, and then testing how well these new mixtures perform under different environmental conditions and structural loads.

In one such project, S&T researchers are studying the behavior of high-performance concrete with adapted rheology (HPC-AR). Rheology involves flow behavior of the material that cannot be measured with traditional workability test methods. HPC-AR is targeted for the construction of bridges, airports and rail systems, port and harbor facilities, and nuclear power plants.

"Unlike conventional concrete, HPC-AR such as self-consolidating concrete (SCC), requires less consolidation and uses new materials to properly fill the formwork," says Khayat. "This new class of HPC can lead to quicker construction, a greater level of automation and improved productivity."

The researchers are also investigating ultra-HPC, which has a compressive strength five to 10 times that of conventional building materials, and eco-crete, which contains a high volume of recycled materials.

Working with Missouri S&T's researchers, the Missouri Department of Transportation used eco-crete with up to 40 percent recycled concrete aggregate (RCA) to build a portion of the approach to the Stan Musial Veterans Memorial Bridge in downtown St. Louis. They used RCA recovered during the renovation of Lambert-St. Louis International Airport.

MoDOT built a 22.5-foot-wide ramp in four sections: a control section made with conventional concrete,

and three other sections made with concrete that incorporated different levels of RCA.

Missouri S&T researchers are monitoring the structural health of the eco-crete using vibrating wire strain gauges embedded in the pavement. They hope to demonstrate that this environmentally friendly concrete can perform well in the long term.

"Our main objective with eco-crete is to use at least 50 percent recycled materials, including industrial by-products, to reduce the cement content needed to make concrete. This will reduce the embodied energy and carbon footprint of concrete production," says Khayat. "It is also an effective way to reuse waste generated from demolitions — to keep it out of landfills and conserve non-renewable natural resources."

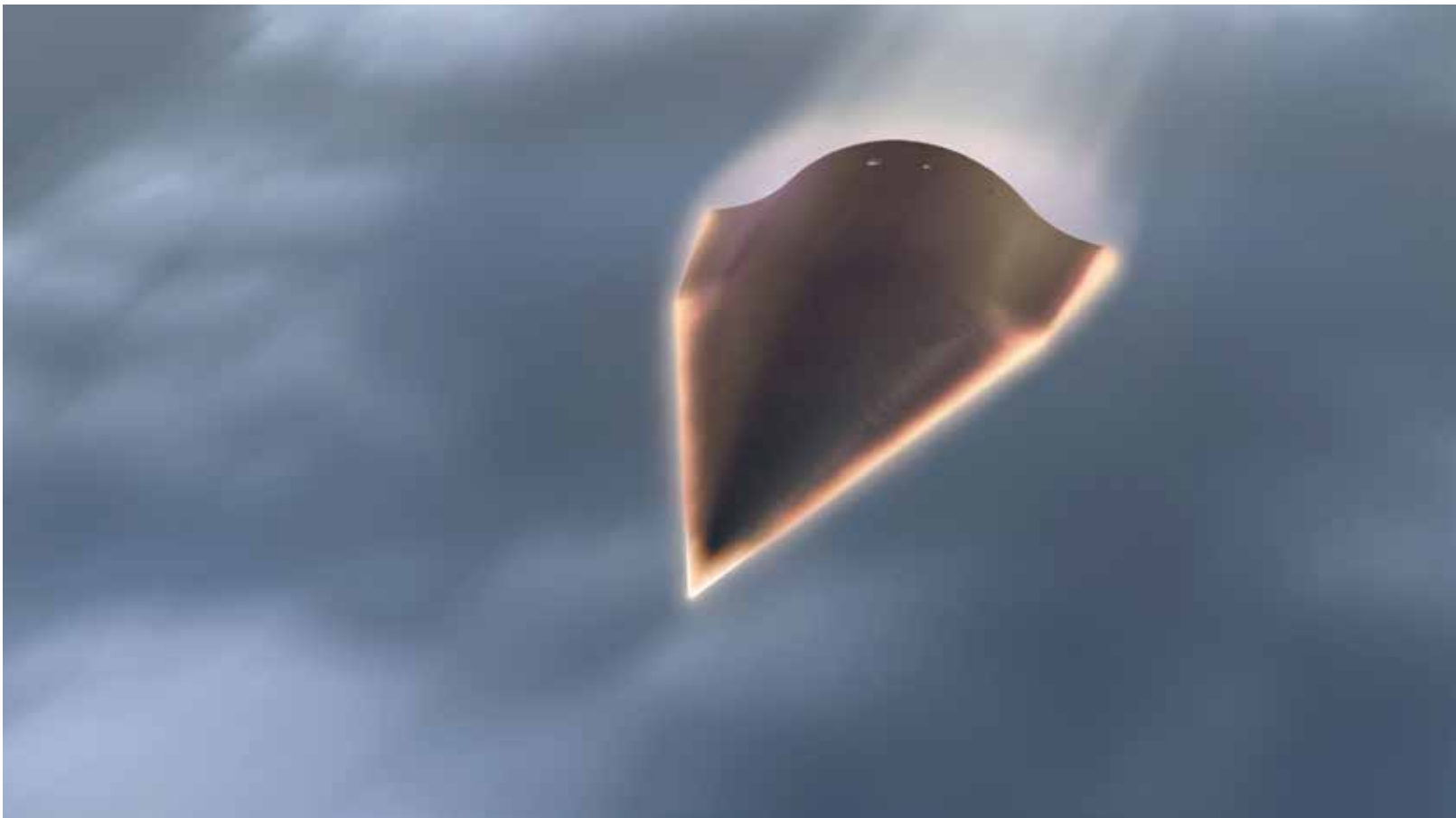
One of the weak links in concrete is the quality of the interface between the hydrated cement paste and aggregate. Missouri S&T researchers are investigating ways to strengthen concrete by coating coarse aggregate with materials-engineered polymers before adding them to the cement mortar.

"The polymer molecules strengthen the contact with tether groups that act like a glue, as barriers to cracking between the aggregate and matrix," says **Thomas Schuman**, associate professor of chemistry. "Polymers have entanglement — it's a bit like trying to remove one string of Christmas lights from a bunch — long cords with knobby protrusions."

Schuman hopes to improve the strength of the matrix-aggregate interfaces to create tougher composite material that resists cracking, performs better structurally and has a longer service life.

"Concrete initially contains a lot of water to hydrate the matrix and bond with the aggregate," says Schuman, but the bond can be porous and weak. "Polymers bond well to both the aggregate and the matrix and fill voids, so they can reduce the concrete's porosity and add strength and flexibility to reduce crack initiation and propagation."

Schuman is working with **K. Chandrashekhara**, Curators' Professor of mechanical and aerospace engineering, and **Jeffrey Volz**, assistant adjunct professor of civil, architectural and environmental engineering, to evaluate the engineering properties of the novel polymer-modified concrete. ■



Extreme engineering

Bill Fahrenholtz and **Greg Hilmas** are testing the thermal and mechanical properties of ceramics to find out what makes them stronger. The two Curators' Professors of ceramic engineering lead the Enabling Materials for Extreme Environments signature area.

Tell me about extreme environments.

/// **F** We are interested in many different extremes — temperature, radiation environments like in nuclear applications or even extreme mechanical loads. Chemical reactivity as well.

You can't weld ceramics, right?

/// **F** Well, we are. In plasma arc welding, the arc is like a continuous bolt of lightning running from your welding tool that generates enough heat to melt a material and fuse two pieces together. A ceramic material has to be electrically conductive or the arc won't be stable enough to heat properly. If you don't have the right thermal conductivity, you'll thermal-shock your material into a bunch of little pieces instead of welding it.



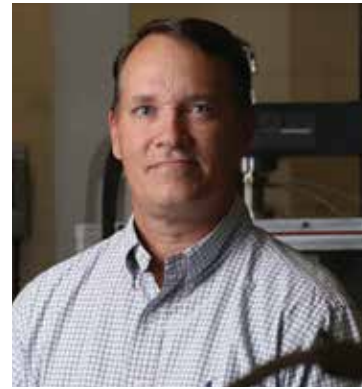
Hypersonic flight

Hypersonic vehicles like the U.S. Falcon (pictured above), which is capable of flying at 13,000 mph, must be able to withstand ultra-high temperatures. Missouri S&T researchers are working to develop ceramics that can take the heat and could one day be used in the leading and trailing edges of hypersonic vehicles.





Bill Fahrenholtz is a Curators' Professor of ceramic engineering at Missouri S&T.



Greg Hilmas is a Curators' Professor of ceramic engineering at Missouri S&T.



/// H In thermal shock, you change the temperature of a material too quickly. If you take a drinking glass out of a hot dishwasher and fill it with ice water, you're cooling the inside too quickly, but you still have hot glass on the outside. You've created a stress distribution through the material that it doesn't like. Basically you're transferring more tensile stresses to the atoms in and around that stress and it breaks. When you do the reverse — when you heat a material too quickly — the result tends to be even worse.

How do you avoid thermal shock?

/// H To weld ceramic material we preheat it to close to half of its melting temperature. If we try to just nail it with that lightning bolt of electricity that Dr. Fahrenholtz mentioned, it heats too quickly and cracks.

But why would you want to weld ceramics?

/// H Ceramics are difficult to make complex shapes out of. They're hard, so they have to be machined with a diamond cutting tool and that's expensive. We're making leading edges for hypersonic aircraft. In the old days, we would have taken a block of ceramic material and machined it into the shape we're looking for. We've demonstrated that you can take two plates, put them together at the right angle and just weld the tip. We're working on basic research here. It's like where the steel industry was decades ago.

/// F It's no different than steel, like Greg said. Some grades of steel alloys are specifically designed to be weldable and others are difficult or impossible to join that way. We just have to find the right combinations of ceramics with the characteristics we need. It's all part of the research. This is a unique case. With the exception of glass, most ceramics aren't designed to

melt and resolidify. People usually don't melt things like zirconium diboride that we're working on because its melting temperature — 3,250 degrees Celsius — is just so high.

How can tiny ceramic tiles help stop thermal shock?

/// H We're refining technology developed when I was at the University of Michigan, but using zirconium diboride to make ultra-high-temperature ceramics using an architecture that looks like a ceramic tile floor. You want your ceramic tiles to be surrounded by a material with dramatically different properties — like the grout in a tile floor, only at the microscopic level. If you've dropped something heavy on a ceramic tile floor, you know that a crack usually stops at the grout. That's because the grout is porous and naturally blunts cracks. It's like what we're doing with this. The cracks in our sample stop in a single cell — or tile. By creating this weaker cell boundary phase — the grout, if you will — cracks run to the cell boundary phase and stop. It provides better wear resistance and boosts fracture toughness, which boosts thermal shock resistance. Take a material with pretty poor thermal shock resistance like zirconium diboride, which usually can withstand an instantaneous temperature change of 400 degrees Celsius before it acts like the glass out of your dishwasher. Using the ceramic tile architecture, we can take that same material to 1,400 degrees Celsius instantaneously without a catastrophic break. We're also looking at different architectures than the traditional tile floor, like spirals, that might be easier to process. We have patented this technology.

/// F We're demonstrating that ceramic materials have useful properties at well over 2,000 degrees Celsius. We're really laying the ground work for learning basic material properties. ■



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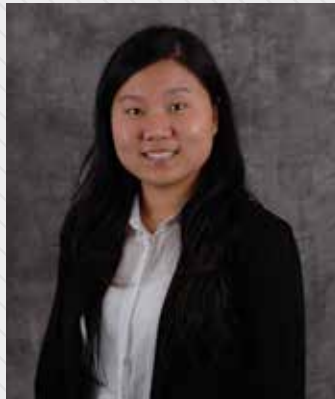
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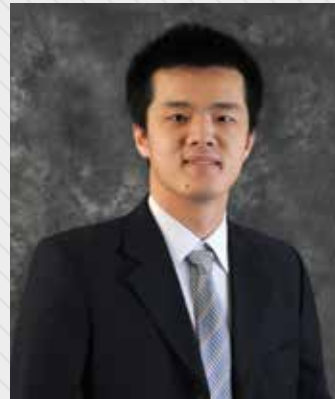
Rising stars



Lian Duan, assistant professor of mechanical and aerospace engineering, received a Young Investigator Research Program Award from the Air Force Office of Scientific Research to study how noise affects wind tunnel testing for hypersonic vehicles. Using the world's largest supercomputers, he studies the physics of noise generation in hypersonic wind tunnels and the effect of the tunnel noise on boundary layer transition. His work can help characterize the natural disturbance environment in hypersonic wind tunnels and improve the testing of hypersonic space vehicles.



Jie Gao, assistant professor of mechanical engineering, was one of 35 faculty members in the nation to win a competitive research grant through the Ralph E. Powe Junior Faculty Enhancement Program. Her research focuses on the way light and matter interact at the nanoscale level. Gao studies the unusual electromagnetic properties exhibited by the interaction between light-emitters and optical metamaterials. Her work could lead to the development of light-emission devices, chip-scale lasers and optical information processing.



Yiyu Shi, assistant professor of electrical and computer engineering, received a CAREER Award from the National Science Foundation to study advanced circuit design. Shi has developed a way to reduce the silicon area of a 3-D integrated circuit by up to 30 percent by making through-silicon vias, or TSVs act as capacitors, inductors or transistors. His research could reduce production cost by up to 70 percent.



Zhaozheng Yin, assistant professor of computer science, received a CAREER Award from the National Science Foundation to develop algorithms and systems for processing microscopy images of biological specimens. Using time-lapse microscopy images, he can record the movement and division of cells, and track changes in their shape and appearance.