PennState
MRI

FOCUS
on MATERIALS

MATERIALS RESEARCH INSTITUTE BULLETIN FALL 2017

ADVANCING MANUFACTURING

PennState

MRI

MATERIALS RESEARCH INSTITUTE

Focus on Materials is a bulletin of the Materials Research Institute at Penn State University. Visit our web site at **www.mri.psu.edu**

Clive A Randall, *Director of the Materials Research Institute and Professor of Materials Science and Engineering*
N-221
Millennium Science Complex
University Park, PA 16802
(814) 863-1328
car4@psu.edu

Robert Cornwall, *Managing Director of the Materials Research Institute*
N-319
Millennium Science Complex
University Park, PA 16802
(814) 863-8735
rgc5@psu.edu

Walt Mills, *editor/writer*
N-358
Millennium Science Complex
University Park, PA 16802
(814) 865-0285
wem12@psu.edu

Krista Weidner, *writer*

Mark Passmore, *graphic design*
Passmore Design
(814) 353-8853
passmoredesign@comcast.net

This publication is available in alternative media on request.

U.Ed. RES 17-81

Message from the Director

Clive Randall

President Eric Barron launched the Invent Penn State initiative in 2015 in order to connect the knowledge of Penn State researchers across the commonwealth with the marketplace and foster an entrepreneurial spirit among faculty, staff, and students. It can be a daunting prospect to cross the divide between academia and business, but a number of MRI faculty have taken the leap, and have experience on how to transition discovery to product. You can read about some of our recent startup companies on our website, mri.psu.edu, under the tab labeled “Innovations” at the top of the page.

Many other MRI researchers are engaged with industry, aiding our mission to maximize the impact of our research endeavor. Discovery in materials science can be through new structures, new properties, new composites, and new understanding of materials from properties to the synthetic pathways. The ability to take this knowledge and scale to large-scale processes and production enables the discovery to have a viable societal impact, provide new products and new devices, and to develop new competitive business. This can be done in partnership with established companies in the form of research partnerships or in the development of new start-ups. Whatever strategy is best, there is risk involved, and the “valley of death” always looms in the investment. Having a faculty with a vision to manage this, and who are also willing to challenge and reinvent the manufacturing sector through new materials and processes, helps in the transition of discovery to product through the various Technology Readiness Levels (TRL’s). As one example, additive manufacturing is one of those processes that is poised to revolutionize manufacturing, possibly even decentralizing the idea of the factory. Here the Penn State University is a clear leader in the field, particularly in manufacturing of metal parts for industry and defense. Be sure to read Prof. Tim Simpson’s remarks on “The Future of Manufacturing” in this issue.

Across our university, we have our commonwealth campuses also working to bridge the industrial and manufacturing gaps, at Penn State Erie, the Behrend College, we have a top 30 undergraduate engineering school with facilities and expertise that are ideal for doing polymer manufacturing research. Their “open laboratory” philosophy invites companies to share space side-by-side in university labs and engages students and faculty in real-world problem solving. Behrend faculty are bringing new tools and techniques to the plastics industry that could provide huge savings to automobile manufacturers and other plastic parts makers. Read about their work in “Behrend Campus Advances Plastics Manufacturing.”

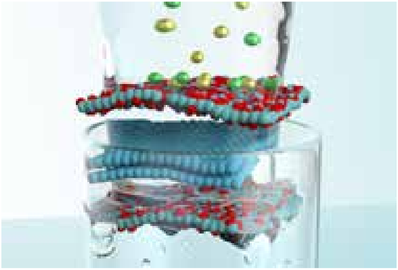
You will find many more examples of the way Penn State and MRI researchers are contributing to the revitalization of manufacturing in this issue, but I want to direct your attention to the Humanitarian Materials Engineering section of the magazine. With MRI support, Prof. Esther Obonyo is initiating a project involving retrofitting historical buildings in New Kensington, with Kevin Sinder and the Commonwealth campus there. We will keep you informed of her progress in future issues. Another model for driving manufacturing is the program with the Applied Research Laboratory, with the site at Freeport, where there is an effort to drive production of textured piezoelectric ceramics for naval sonar applications and other sensor actuator applications.

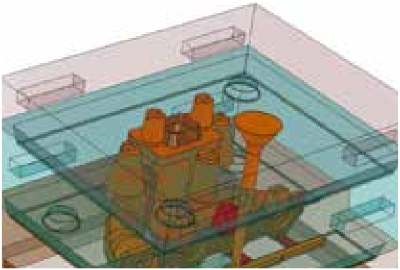
Sincerely,
Clive Randall
Director of the Materials Research Institute
and Professor of Materials Science and Engineering

To access the materials expertise at Penn State, please visit our Materials Research Institute website at **www.mri.psu.edu** or the Office of Technology Management website at **http://www.research.psu.edu/offices/otm**

CONTENTS

IN THIS ISSUE:
ADVANCING MANUFACTURING





Cover image: Bigstock

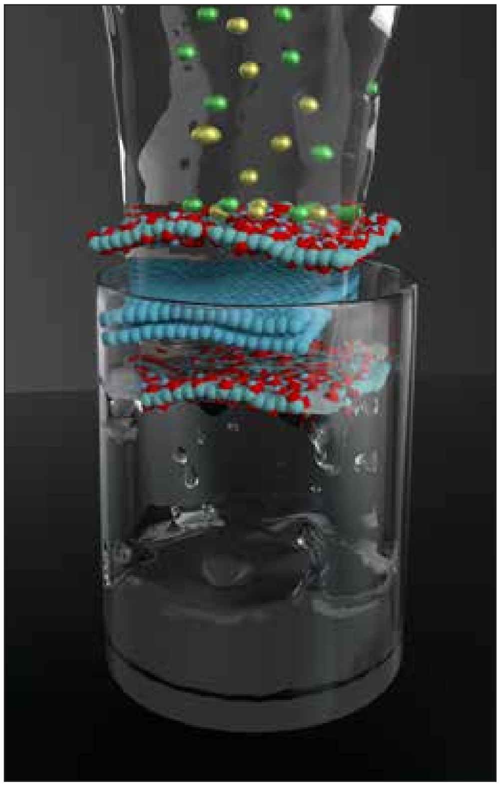
Snapshots are brief summaries of significant materials-related breakthroughs by MRI researchers.

TOWARD A SMART GRAPHENE MEMBRANE TO DESALINATE WATER

An international team of researchers, including scientists from Shinshu University (Japan) and the director of Penn State's ATOMIC Center, has developed a graphene-based coating for desalination membranes that is more robust and scalable than current nanofiltration membrane technologies. The result could be a sturdy and practical membrane for clean water solutions as well as protein separation, wastewater treatment, and pharmaceutical and food industry applications.

"Our dream is to create a smart membrane that combines high flow rates, high efficiency, long lifetime, self-healing, and eliminates bio and inorganic fouling in order to provide clean water solutions for the many parts of the world where clean water is scarce," says Mauricio Terrones, professor of physics, chemistry, and materials science and engineering, Penn State. "This work is taking us in that direction."

The hybrid membrane the team developed uses a simple spray-on technology to coat a mixture of graphene oxide and few-layered graphene in solution onto a backbone support membrane of polysulfone modified with polyvinyl alcohol. The support membrane increased the robustness of the hybrid membrane, which was able to stand up to intense cross-flow, high pressure and chlorine exposure. Even in early stages of development, the membrane rejects 85 percent of salt, adequate for agricultural purposes though not for drinking, and 96 percent of dye molecules. Highly polluting dyes from textile manufacturing is commonly discharged into rivers in some areas of the world.



A scalable graphene-based membrane for producing clean water
Credit: Aaron Morelos-Gomez

For the full story, go to **mri.psu.edu/mri/news/toward-smart-graphene-membrane-desalinate-water**

Contact Mauricio Terrones at mut11@psu.edu

Original paper: doi:10.1038/nnano.2017.160

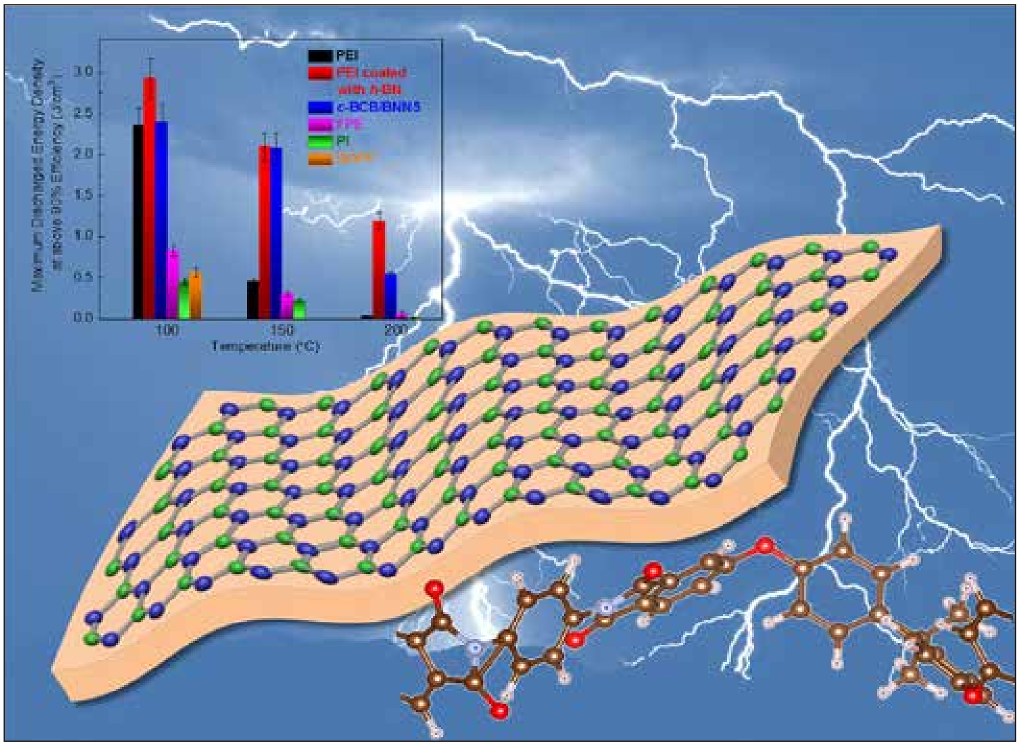
ENERGY STORAGE SOLUTION COMBINES POLYMERS AND NANOSHEETS

A new, lightweight composite material for energy storage in flexible electronics, electric vehicles, and aerospace applications has been experimentally shown to store energy at operating temperatures well above current commercial polymers, according to a team of Penn State scientists. This polymer-based, ultrathin material can be produced using techniques already used in industry.

“This is part of a series of work we have done in our lab on high-temperature dielectrics for use in capacitors,” said Qing Wang, professor of materials science and engineering at Penn State. “Prior to this work we had developed a composite of boron nitride nanosheets and dielectric polymers, but realized there were significant problems with scaling that material up economically.”

Read the full story at Energy Today:
https://www.energytoday.net/technology/energy-storage-solution-combines-polymers-nanosheets/

Contact Qing Wang at wang@matse.psu.edu



PEI coated with hexagonal boron nitride (hBN) nanosheets significantly outperforms competitive polymers at operating temperatures needed for electric vehicles and aerospace power applications.

Credit: Feihua Liu/ Penn State

FAST CAPTURE OF CANCER MARKERS WILL AID IN DIAGNOSIS AND TREATMENT

A nanoscale product of human cells that was once considered junk is now known to play an important role in intercellular communication and in many disease processes, including cancer metastasis. Researchers at Penn State have developed nanoprobes to rapidly isolate these rare markers, called extracellular vesicles (EVs), for potential development of precision cancer diagnosis and personalized anticancer treatments.

"Most cells generate and secrete extracellular vesicles," says Siyang Zheng, associate professor of biomedical engineering and electrical engineering. "But they are difficult for us to study. They are sub-micrometer particles, so we really need an electron microscope to see them. There are many technical challenges in the isolation of nanoscale EVs that we are trying to overcome for point-of-care cancer diagnostics."

The team's initial challenge was to develop a method to isolate and purify EVs in blood samples that contain multiple other components. The use of liquid biopsy, or blood testing, for cancer diagnosis is a recent development that offers benefits over traditional biopsy, which requires removing a tumor or sticking a needle into a tumor to extract cancer cells. For lung cancer or brain cancers, such invasive techniques are difficult, expensive and can be painful.

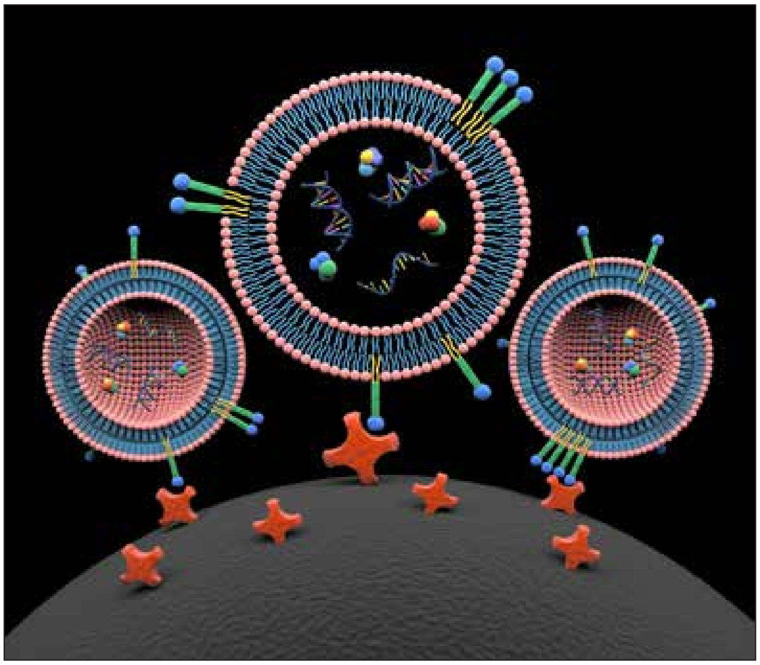
"Noninvasive techniques such as liquid biopsy are preferable for not only detection and discovery, but also for monitoring treatment," says Chandra Belani, M.D., professor of medicine at Penn State's Milton S. Hershey Medical Center and Cancer Institute and clinical collaborator on the study.

How it works

"We invented a system of two micro/nano materials," Zheng says. "One is a labeling probe with two lipid tails that spontaneously insert into the lipid surface of the extracellular vesicle. At the other end of the probe we have a biotin molecule that will be recognized by an avidin molecule we have attached to a magnetic bead."

Read the full story at Penn State News: **http://news.psu.edu/story/461302/2017/04/10/research/fast-capture-cancer-markers-will-aid-diagnosis-and-treatment**

Contact Prof. Zheng at sxz10@psu.edu.

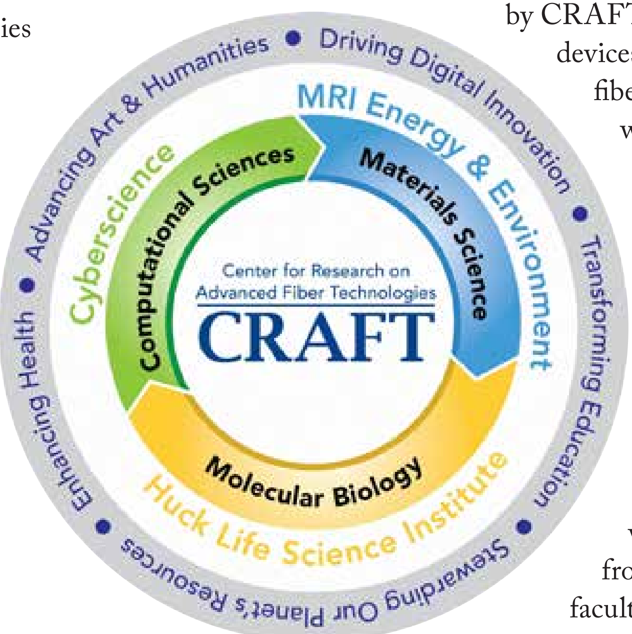


Lipid nanoprobes (blue, green and yellow colored) spontaneously insert into lipid bilayer of three extracellular vesicles. The cargo content of extracellular vesicles includes proteins, DNA and RNA. The lipid nanoprobe-labeled extracellular vesicles are captured onto the surface of a magnetic bead (black, bottom) through interaction with conjugated avidin molecules (red). Exosome isolation and its cargo analysis offers new opportunities for a diverse range of molecular analyses, including mutation detection from blood plasma of cancer patients.

Image: Xin Zou/Penn State

INAUGURAL CRAFT CENTER WORKSHOP HIGHLIGHTS FIBER TECHNOLOGY

The textile industry in the US is making a comeback after a decades-long slump. Crucial to the resurgence of textile manufacturing in America is investment in advanced fiber technologies that add value to traditional textiles. The new Center for Research on Advanced Fiber Technologies (CRAFT) at Penn State's Materials Research Institute is applying the expertise of materials scientists, molecular biologists, and electrical and computational engineers, in collaboration with artists and designers, to develop a textile industry that is competitive with the rest of the world, based on new functionalities in fibers.



"CRAFT is about the next generation in textiles and devices," said center director Melik Demirel, Penn State professor of engineering science and mechanics, introducing the new center at the Programmable and Wearable Molecular Composites Workshop on March 21 in State College. "We are at 26 faculty and growing at Penn State, from 15 different departments."

CRAFT is part of AFFOA, Advanced Functional Fabrics of America, one of the 14 Manufacturing USA consortia. AFFOA's strategy is to "create a national network of 'advanced fabric' startup incubators and connect them with market facing companies to enable exciting product ideas to emerge across the country." CRAFT is partnering with two other Pennsylvania universities, Drexel and Carnegie Mellon, to bring an AFFOA Fabric Discovery Center to the commonwealth. Drexel is the lead university.

CRAFT affiliates include a diverse range of manufacturers, including chemical, clothing, automobile and furniture companies, two dozen universities, and numerous small technology companies and nonprofit organizations.

Among the research areas already being pursued by CRAFT faculty: wearable textile devices and tattoos, 3D printable fibers, programmable fibers with embedded electronics, metamaterials-based fibers for cloaking and camouflage, self-healing and self-cleaning bio-inspired fibers, and medical fibers for controlled drug delivery, tissue repair, and wound care.

The initial CRAFT workshop drew interest from industry as well as faculty from other universities. In all, 65-75 attendees registered for the two-day meeting to hear talks from clothing designers, physicists and engineers, and a roundtable discussion featuring university, government, and industry representatives. Topics ranged from wearable design to shape memory fabrics to atomically thin coatings. As Genevieve Dion, a clothing designer and associate professor from Drexel, told the audience, "Functional textiles are said to be the most transdisciplinary research area of our time."

Penn State's CRAFT will complement Drexel's long-standing textile program with Penn State's strength in materials science and engineering to take advantage of a manufacturing sector that is poised to grow, according to AFFOA, by $50 billion over the next 10 years.

Visit the CRAFT website to see how CRAFT technologies can advance innovative textile products for your company. **https://www.mri.psu.edu/mri/facilities-and-centers/craft**

MORGAN ADVANCED MATERIALS PARTNERS WITH PENN STATE

At the World Conference on Carbon, held at Penn State in 2016, Mike Murray, Chief Technology Officer at Morgan Advanced Materials, revealed that their new Center of Excellence would be located in Innovation Park at Penn State, placing it in close proximity to the university's top talent and facilities. Over the course of three years, Morgan is expected to make a major investment aimed at establishing a truly world-class research facility. Once operational in early 2018, the center is expected to create a range of highly-skilled research posts over the next few years.

"For us, the decision to work with Penn State was a natural one," said Murray. "As a world leader in carbon-related research, Penn State has an unrivalled reputation for innovation in its field, which we believe will add real value for our customers. The partnership will help accelerate our development of new products and capabilities, enabling us to continue to meet the future needs of our customers more quickly, efficiently, and comprehensively."

Products by Morgan Advanced Materials find their way into a number of applications, including ultra-lightweight combat helmets, electric vacuum pumps in cars, and ultrasonic flow sensors.

Image: Morgan Advanced Materials

Esther Obonyo Wants to Break Down Barriers to Low-Cost Local Building Materials

Esther Obonyo calls herself a Nairobi girl. The former interim director of Penn State's Humanitarian Engineering and Social Entrepreneurship (HESE) program and Penn State's Inaugural Global Faculty Fellow is relatively new to Penn State but has long research ties to Africa and particularly to Nairobi, Kenya, where she was raised and where she earned her initial degree, in building economics (Quantity Surveying). Following graduation from University of Nairobi, Obonyo worked for an American construction company in Kenya before moving to England to further her education. She earned a Masters in architecture and a Ph.D. in civil and building engineering. She then went to work in the private sector in the innovation department of a large multinational construction firm. She is an associate professor of engineering design and architectural engineering. Prior to that she was at the University of Florida.

This combination of training and work experience has given her a rather rare perspective on what is needed to overcome barriers to solving the large-scale building deficit in African countries.

"The big problem, in my opinion, is that the pathway to scale has still not been identified," Obonyo says. "Nobody has said, 'Here is the solution, and we can repeat it at the scale of say, 100,000 or a million.'"

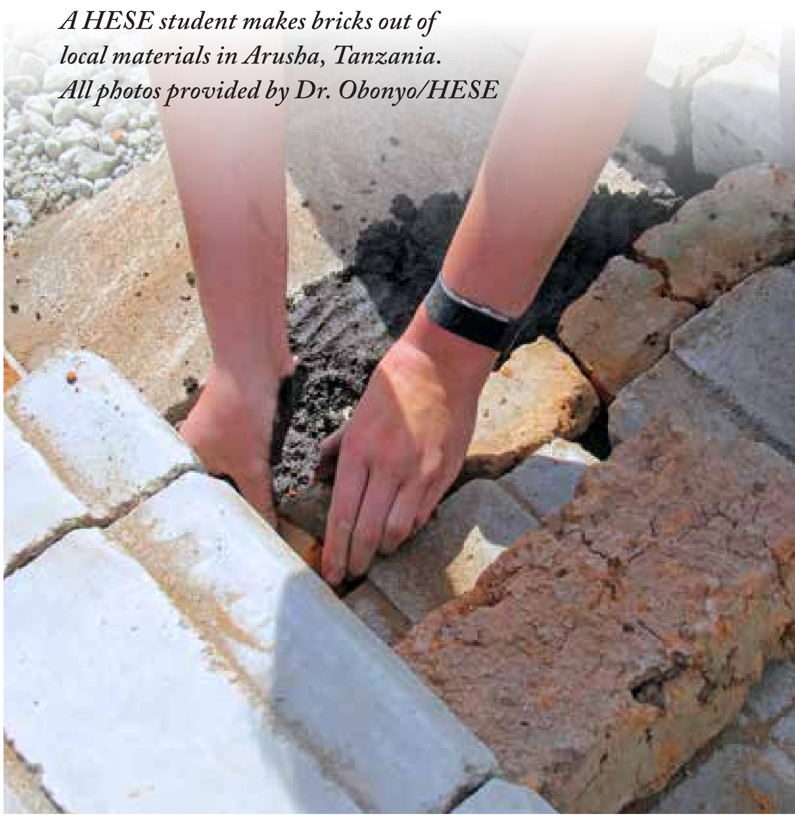
Because her training and professional experience straddle the architectural design and the building engineering divide, she can bring an analytical perspective to a design challenge. In addition, experience working in collaboration with local business and governmental organizations makes the financial and regulatory aspects of introducing new building materials more tractable.

Since 2008, Obonyo has been doing research in sustainable structural materials for building applications in both Kenya and Tanzania.

"Whenever I come to Kenya, I have the same question in my mind. A lot of people have done research on affordable building technology and building materials, but none of it seems to have had an impact," she says. "We can just say we are not going to solve this, or we can go ahead and try looking at it from another perspective."

A big issue, according to the local professionals she has met in Nairobi, was the requirement that nonconventional materials comply with building codes. That provided an opportunity for Obonyo and her colleagues, because questions of strength and durability can be tested.

"The construction industry has a problem incorporating new materials because we can't demonstrate compliance



A HESE student makes bricks out of local materials in Arusha, Tanzania. All photos provided by Dr. Obonyo/HESE with the existing provisions of building code that were written with time-tested materials such as concrete," she says. "That's something we can investigate through a basic science approach."

There is some empirical data demonstrating that if the unconventional material, primarily soil, is designed properly and scientific measurements are made to inform the inclusion of binders and other additives, they can be used to make affordable building materials that can perform up to code. Nevertheless, they are seeing some mixed results, some of which could be attributed to process-related factors.

For example, most tests in the field are based on rules of thumb that have been in use for a hundred years.

HESE students with Dr. Obonyo

One rule that has a scientific basis is not to use the top layer of soil because the surface layer is high in organic material. The testing method typically used for quality control is to put the soil in water in a bottle, shake it, and see how the various particles break down. Such tests work fine for understanding from a big picture perspective if the clay/sand content is adequate. This test will not provide the sort of information that is necessary to make a decision on whether to use cement and/or lime as a binder. Some of the reported variations in the performance of the non-conventional materials can be attributed to the lack of soil-DNA type of information.

"There are people making low-cost houses with non-conventional materials like these, and it works just fine for meeting the needs of, say, 250 to 500 people," she says. "But these processes cannot be easily translated into sustainable housing solutions at scale. If we are going to produce the amount of brick we need to reduce the current housing deficit, then we need cross-disciplinary thinking."

Humanitarian Engineering

Cross-disciplinarity is a hallmark of the HESE program at Penn State, which draws its students from across the university. Typically, about half the students are in engineering, with the rest spread across the other colleges. In May, Obonyo and Dr. Sarah Ritter, a faculty member from the Engineering Design program, took a group of 17 students to Arusha, a city of around half a million located in northern Tanzania, for a three-week work experience.

"Before going, the students do guided research in a hands-on, studio-like setting. I provided a lot of background information to level the playing field for them given that the HESE program is by design a melting point of students from different academic backgrounds," Obonyo says.

The cross-disciplinarity in HESE is exemplified in one student project that focused on food security, specifically, building facilities for storage and distribution of food that otherwise might be wasted through spoilage. This was inspired by her experiences as a Jefferson Science Fellow in Washington, D.C.

"We largely talk about food insecurity in terms of producing more food, yet there is a large amount of food wasted through post-harvest loss because of the lack of adequate storage facilities," says Obonyo. "So, for one of the student projects I wanted them to look at the opportunity of creating a low-cost storage facility that leverages the properties of organic building materials and other passive design techniques."

Organic roofing material is known to passively cool a building's interior. The walls were made 80 percent of earth and 20 percent or less of concrete. There is an additional ecological benefit here. Concrete is too

expensive for many to afford, and its processing is a major contributor to greenhouse gas in the atmosphere.

“The students spent the Spring semester using an engineering design process to scope the project,” Obonyo explains. “They came up with some proofs of concept and during the three weeks of Maymester 2017, we travelled to Arusha to test and validate the concepts. For the post-harvest loss, this was partly done through the construction of a passively ventilated unit. Although we didn’t have time to finish the structure, by the time we left it was evident to everyone that the temperature inside the four walls minus the roof was significantly lower than outside.”

Another hallmark of the HESE program is working with locals to create sustainable long-term solutions. From the beginning, Obonyo was in regular communication with people in Arusha, putting options in front of them and soliciting feedback and opinions. Understanding cultural norms and practices is made easier for her by knowing the language, but it is also important for the students to spend as much time as possible interacting with local people. “You start to pick up unspoken things,” she suggests. “My East African people communicate a lot of things through the use of the unspoken word.”

Working with materials scientists

“When I came to Penn State, I already had this niche in mind that there is a role that science and technology can play in addressing societal problems,” Obonyo says. “In business, the biggest barrier I saw to sustainable solutions at scale was lack of quantifiable knowledge. I did my Ph.D. in intelligent systems and data mining. I still use it in my research. But it’s all part of knowledge management, knowledge distribution.”

She has experience working with materials scientists in testing samples she has brought back from East Africa, but she wants to expand that into other areas. With the support of the Materials Research Institute, she has begun a project with the chancellor of Penn State New Kensington to retrofit several historical buildings using lower cost, innovative materials. They are exploring several options that can optimize the hygrothermal (heat and moisture) performance of the roofing element in a way that contributes to the goal of energy-efficient building systems at a neighborhood level.

“We need to be able to replicate this at large scale in order to affect an entire community. There may be 100 buildings that need help in a rapid and cost-effective way,” she says. “But it’s like Tanzania or Kenya, you have to ensure that the material you come up with complies with building codes. And when retrofitting something that is already damaged, how do you ensure that the solution is not going to deteriorate rapidly? That requires a multidisciplinary approach. I hope to have a long, 30-year relation with materials science.”

For further information about Prof. Obonyo’s research, contact her at eao4@engr.psu.edu.

Prof. Eugene Park with Dr. Esther Obonyo in Arusha, Tanzania

THE FUTURE OF MANUFACTURING

Image Credit (2): Bigstock

There is a something new going on when it comes to American manufacturing. After a major decline in the first decade of this century, more than 800,000 manufacturing jobs have been added in the manufacturing sector since 2010, when the Great Recession began to ebb. In that time, manufacturing has grown at nearly twice the pace of the economy as a whole.

Some of the resurgence in manufacturing can be attributed to low energy costs, particularly due to unconventional natural gas extraction, but other factors, such as the rise in worker salaries in China, long and unstable overseas supply chains, and the benefits that accrue from the proximity of designers to production facilities, have contributed to the phenomenon of reshoring — manufacturers moving back to the U.S. Approximately 265,000 jobs have returned to the U.S. since 2010. But for the most part, low-skill jobs are not the ones that are returning. The new jobs in manufacturing will require knowledge-based skills and digital savvy.

The next stage in manufacturing

There is a renewed interest in manufacturing in the U.S. and in U.S. universities, says Dr. Timothy W. Simpson, the Paul Morrow Professor of Engineering Design and Manufacturing in Penn State's Department of Mechanical and Nuclear Engineering. "People refer to it as 'advanced manufacturing,' and rightly so," Simpson says, "because it brings to bear the latest technologies, including digital design, virtual and augmented reality, advances in robotics and automation, and the internet of things, when all of our machines are going to be able to communicate with one another, including the machines on the factory floor."

In 2011, the Obama administration began a program to build a network of advanced manufacturing institutes that could revitalize moribund industries, such as textiles, or promote emerging industries, such as additive manufacturing/3D printing. Called Manufacturing USA, these government/university/industry partnerships have attracted well over 1,300 companies, universities, and nonprofits as members, in 14 geographically dispersed institutes.

Penn State has been a founding member of three of these institutes: America Makes, designed to make the U.S. 3D printing industry more competitive; DMDII, utilizing digital technologies for manufacturing and design; CESMII, focusing on clean energy and smart manufacturing innovation; and AFFOA, an institute to develop an advanced fiber and textile industry in the U.S.

America Makes is represented at Penn State by CIMP-3D, the Center for Innovative Materials Processing through Direct Digital Deposition. This center brings together the materials, design, computational modeling, and processing expertise of more than 40 Penn State scientists and engineers to develop a basic understanding of the physics of additive manufacturing technologies, and to provide undergraduate and graduate training and workforce development in a multidisciplinary setting. Simpson and the team just launched a new graduate program in Additive Manufacturing & Design (http://AMDprogram.psu.edu) that capitalizes on these strengths to address the growing industry need for education and training.

Simpson, who is co-director of CIMP-3D, also led the College of Engineering's thrust area on advanced manufacturing in their most recent strategic plan.

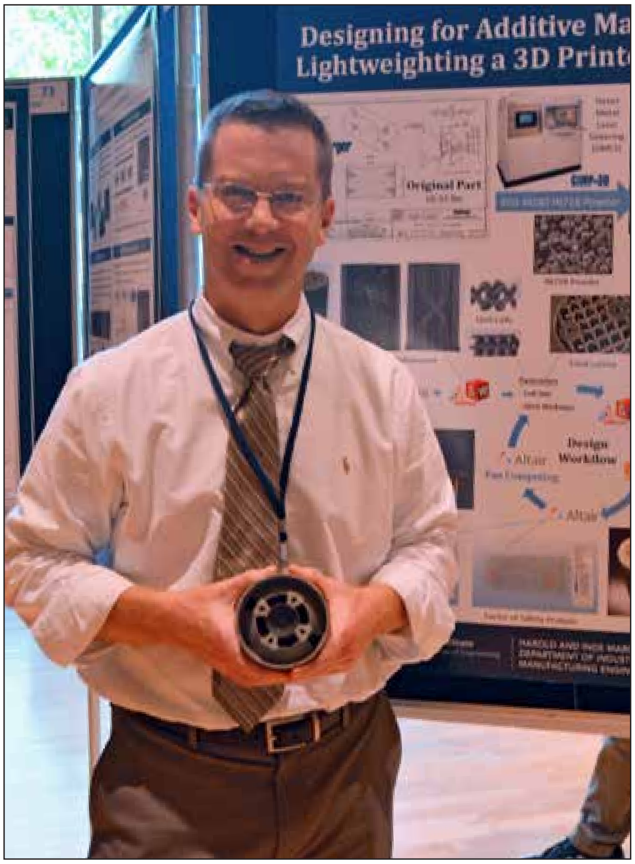
His committee recognized that there are pockets of deep expertise across the university, and some centers of real strength, such as within CIMP-3D and the Materials Research Institute, but much of the advanced manufacturing activity is bottom-up and uncoordinated.

Simpson explains: “The Venn diagram we had in our report was made up of three parts: manufacturing processes, design, and materials. There are really impressive things going on at the intersection of each of those areas, from Clive Randall’s low-temperature sintering process, which is manufacturing and materials, to 3D printing, which is design and manufacturing, to bioprinting, which is also design and manufacturing with new materials”.

“Engineering can’t do this on its own. We need the materials folks, the design folks, and the artists and architects pushing new applications. For example, the technology is available to 3D print houses out of concrete. What could that do in regions that get hit by a flood like Houston just did or are trying to redevelop? We have got the technology now to ask, If we have a new material, what are the design possibilities? Because manufacturing technologies have advanced to this point, the economics changes, the applications change, the supply chain is rewritten or dismantled.”

For Simpson, advanced manufacturing is a synergy of the three parts: processes, design, and materials. That is where Penn State is very well positioned to make rapid progress, he says. This Advanced Manufacturing issue of *Focus on Materials* will highlight some of the faculty expertise that is beginning to accelerate the resurgence of manufacturing in America.

Contact Prof. Simpson at tws8@engr.psu.edu



Tim Simpson holds a 3D printed metal part during a Materials Day poster session. Credit: MRI

BEHREND CAMPUS ADVANCES PLASTICS MANUFACTURING

Penn State Erie, The Behrend College, is secluded in its wooded setting a few miles from the blue-collar industrial city of Erie, Pennsylvania. Behrend takes pride in the practical hands-on approach to educating a cohort of trained graduates ready and eager to work in advanced manufacturing environments at Apple, Boeing, Tesla, and other major companies.

It is a primarily undergraduate campus with a few master's programs, including the Master's in Manufacturing Management, a cross-cutting collaboration between the School of Engineering and the Black School of Business. The undergraduate Interdisciplinary Business with Engineering Studies major in the Black School of Business requires two years of engineering mathematics and science to prepare students to work in the business side of a technical company.

The science of plastic manufacturing

Dr. Alicyn Rhoades, an assistant professor of engineering at Penn State Behrend, is immersed in the culture of plastics manufacturing, with a background in various roles in industry before joining the Penn State faculty. But she is also advancing the science of plastics

The Manufacturing and Innovation Center at Knowledge Park. Credit: MRI

Alicyn Rhoades (left) and Nichole Wonderling in MRI's X-ray Diffraction Lab
Credit: MRI

manufacturing, supported by a five-year, $500,000 CAREER grant from the National Science Foundation.

"Right now, in manufacturing of anything polymeric, the process is often simulated on a computer before any physical parts are actually made," Rhoades explained. "Because of the intricate geometries and expensive machining required to physically make a steel mold or die in which the polymer will solidify, the costs are outrageous. So it's best to simulate the mold-filling first, to make sure the mold design will work."

For example, for a relatively simple part of an automobile, such as a back bumper with some curvature, a mold can cost around $700,000. Prototyping several versions of the part using a steel mold would add several months to the production schedule.

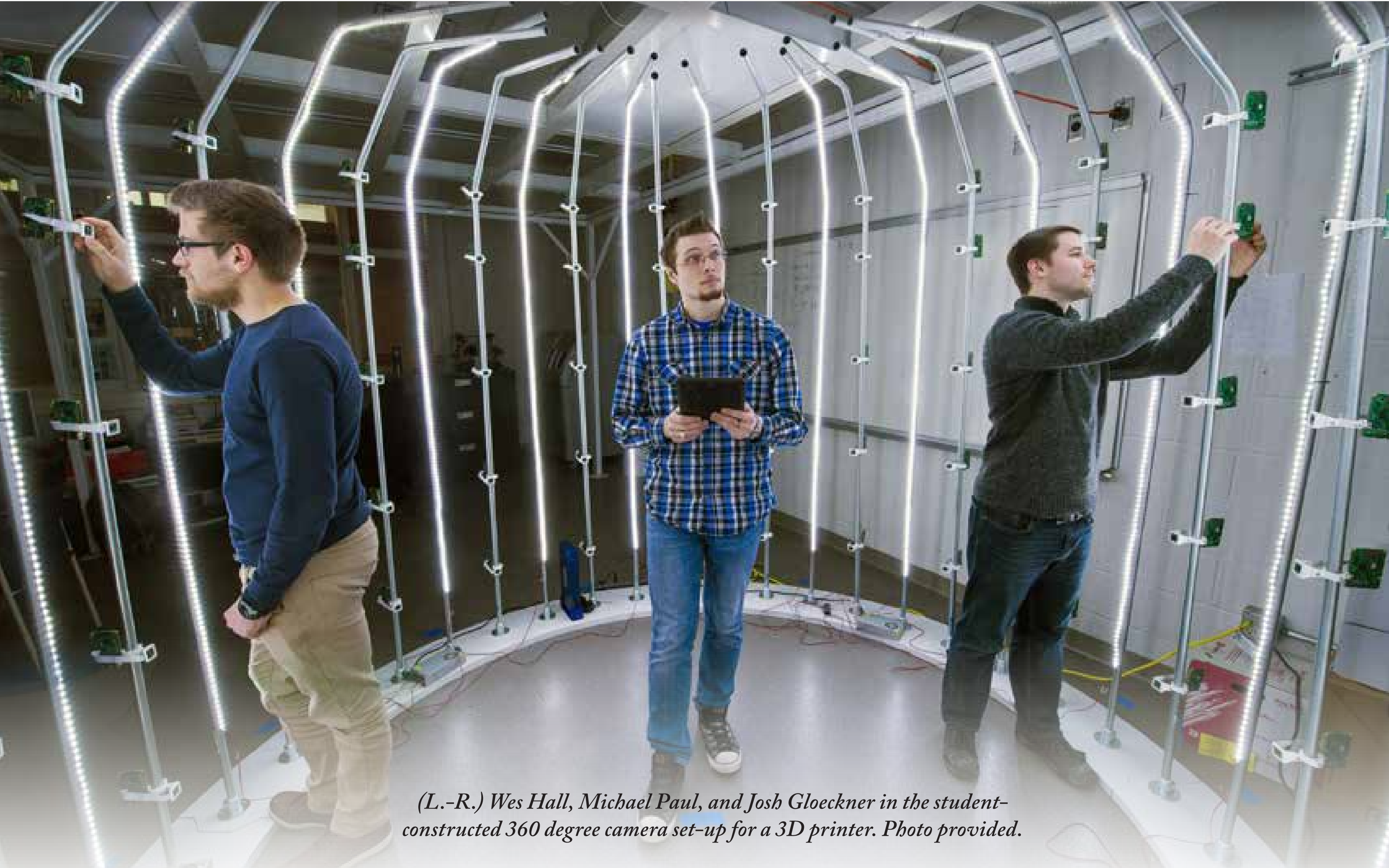
"Companies are losing time and money on their iterative processes. They need more accuracy in their manufacturing simulation and that's why they come to us."

Rhoades said that it is the nature of polymeric materials to shrink and warp as they transition from the melt stage to the solid stage. This can be a critical problem in aerospace and medical applications where precision is crucial.

As many plastics manufacturing gurus will explain, for decades the manufacturing process of polymer injection molding has remained more art than science. Rhoades and her team are bringing science into the process.

"For the past 80 or so years, polymer crystallization has been studied as if the polymer were formed in a melted puddle, as if no other forces except gravity were affecting the final shape. Researchers would heat the polymer to its melting point and watch it cool under a microscope. Relatively little attention has been given to the effects of shear flow on the polymer," she said.

That's not how it works in the manufacturing process. Under pressure and subject to shear forces, everything



(L.-R.) Wes Hall, Michael Paul, and Josh Gloeckner in the student-constructed 360 degree camera set-up for a 3D printer. Photo provided.

about the solidification process changes. Yet the math developed to predict polymer crystallization has not progressed to account for a dynamic process. Collaborations between Rhoades group and Dr. Ralph Colby's group (UP-MatSE) are underway to develop new models that account for flow factors as well as rapid thermal changes that can create gradients in the final product.

"When hot plastic hits cold steel, it cools really fast. Traditionally, polymer crystalization is studied at a cooling rate of 10 degrees C per minute. We are studying solidification between 1000 and 10 degrees C per second. That makes a big difference," she said.

By plugging in the flow factor and the rapid thermal transfer factor into their simulations, the results change dramatically and start to look like what actually takes place in a manufacturing setting. This could potentially save companies such as GM or SKF many weeks of iteration and many tens of thousands of dollars on each new part. From NSF's standpoint, this work provides a fundamental understanding of a process that could be applied to multiple types of manufacturing.

"NSF cares about the impact of their research investments on the economy. We can draw a pretty direct line between what we are doing and the impact it can have," Rhoades said.

Behrend's open-lab philosophy

Amy Bridger is the senior director of Corporate Strategy and External Engagement at the Behrend campus. She is responsible for the interactions between Behrend and the corporate world, including partnerships between companies and Behrend's research programs.

"Behrend has a long history of applied research," she said. "We've been trying to formalize that in something called the 'open laboratory.' It's a philosophy where we have a strong focus on engaging our faculty and

students with industry to grow our programs. We find that our undergraduates, if they are well mentored by faculty, have tremendous capability to develop products and services and perform a research function, even on a baccalaureate level."

Behrend's research park, called Knowledge Park, brings manufacturing companies, both small and international in scope, into a close relationship with faculty and students. In the newly opened Advanced Manufacturing and Innovation Center, a 60,000 square foot building that houses the mechanical and industrial engineering faculty, half of the space is allotted to industry tenants.

"In 2010-11, we decided to take a more active role in the Park and tie it to our mission of teaching and research," Bridger said. "We've tried in our open lab initiative to reduce the barriers to working with industry."

With around 1500 students, Behrend's School of Engineering is the largest at the 4700-student campus and the second-largest engineering school in the Penn State system, according to Greg Dillon, professor of engineering and a faculty member of the Materials Research Institute.

"This industry connection started 20 years ago with capstone projects for seniors," Dillon said. "A $1500 donation to the school funds maybe three students working on an industry project. Capstone Design has over 70 projects each year. It's similar to the Learning Factory at University Park."

Open-lab innovation at Behrend means they are open to working with business. And although companies can be present in the engineering labs, the students need to have a learning experience and do the research themselves. "They have to discover and create something," Dillon explained.

IP policy attracts companies

Since Penn State as a university decided to change its intellectual property policy to be more attractive to industry, Behrend has seen the fruits of that change to a far greater extent than anywhere else in the University.

SKF, the largest bearing manufacturer in the world, decided to open its first US-based innovation center in Knowledge Park. TruckLite, a company that manufacturers truck lighting, opened an Innovation Center at Knowledge Park in order to be close to Behrend faculty members.

"We have the largest academic plastics lab in the U.S., likely the world," Bridger said. "And what's nice about that lab is that it derived from industry wanting a program, and then we built a lab to support the curriculum that industry had asked for."

With the recent addition of a $900,000-plus environmental scanning electron microscope (ESEM), acquired through a proposal to the National Science Foundation by Dillon, Rhoades, and science faculty, the Behrend campus will provide a resource unique to the region.

"Lord Corporation, which has an amazing R&D facility in our area, doesn't have anything like this," Bridger said. "We encourage companies and other universities to come in and use that instrument."

The ESEM has the capability to be used in both science and engineering, to look at live biological samples or to study nanoscale defects in polymers, for example.

"We keep a long list of the equipment that industry say they need. If enough companies show an interest and it fits with the curriculum, that's what we will focus our grants on. Our vision is that if we get these key pieces of equipment, we can draw in a lot of companies to work with us at Knowledge Park," Bridger said.

Contact Prof. Rhoades at amh234@psu.edu.
Contact Amy Bridger at aeb20@psu.edu.
Contact Prof. Dillon at gpd3@psu.edu.

NANOTECHNOLOGY FOR AEROSPACE

Namiko Yamamoto
with 3D printed model
Credit: MRI

The problem of scale is unavoidable when talking about applying materials made in a laboratory into an industrial process. It's one thing to make small transistors with submicron features, but what if you want to coat the entire surface of a jetliner with a conductive nanomaterial?

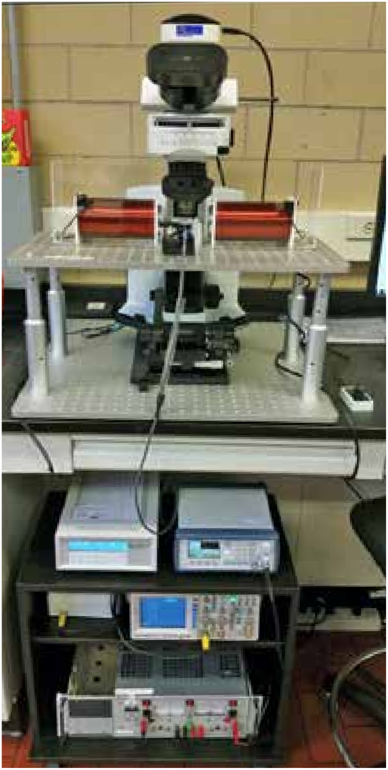
That's the kind of problem Namiko Yamamoto is trying to solve.

"I'm from the Aerospace Engineering Department, and what I want to do is apply nano- and micro-engineered materials to airplanes, satellites, or other large structures," says the assistant professor.

Engineering materials with high quality and functionality at the scale of a microchip or in a thin film is something materials researchers have the expertise to do well, but scaling those processes up to meter and multi-meter lengths is where these laboratory materials run into problems.

The unique properties that occur at the small scale can disappear at larger scale, or the performance of the material degrades with increasing size.

"A lot of the unique properties are coming from nano-scale organization," she says. "If you want to make them larger, those are going to become hard to control. When you go to larger scales you can't



Magnetic assembly of ferromagnetic nano-particles: (left) experimental setup and (right) particle alignment (and thus interphase) tuning by magnetic fields modulation.

Courtesy of Mychal Spencer

enjoy the same degree of performance as the small samples."

In spring 2016, she was awarded just under $380,000 to study scalable manufacturing of multi-functional polymer nanocomposites by the Office of Naval Research.

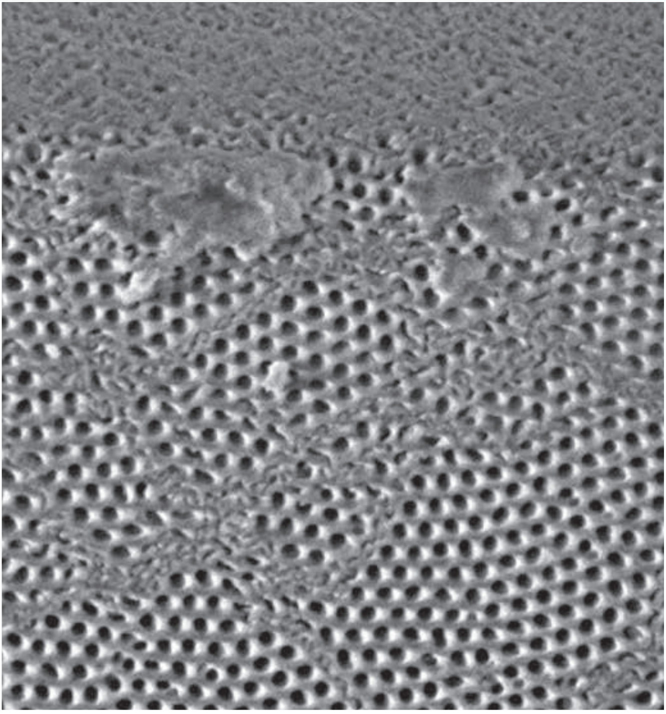
Yamamoto has worked extensively with carbon nanotubes (CNTs) as a potential conductive-coating nanomaterial for use in protecting airplanes from lightning strikes. These nanotubes were aligned, and thus become efficient electrical conductors, like tiny lightning rods. This approach could lead to considerable weight savings over the currently used metal mesh layer. She originally fabricated such material by first organizing the nanotubes and then infiltrating with a polymer; however, this method was not the most scalable. Now, she first mixes nanoparticles together with polymer, and then organizes the nanoparticles using external oscillating magnetic fields.

"We've gained an understanding of the correlation between particle organization and magnetic field frequency," she explains. The difficulty of magnetic particle assembly is that magnetic particles want to stick together. To control and tailor particle patterns, a means to separate particles is necessary, which can be provided by low-frequency field oscillation.

"There are major research players at Penn State who work with acoustic and electric assembly. I like magnetic because it requires low power, as long as the particles are magnetically responsive."

If achieved, the conductive nanoparticle network in such coatings can provide pathways to dissipate current or heat to protect electronics or cargo inside airplanes and buildings. The same network can potentially be used as sensors for nondestructive evaluation and system health monitoring. As an example, in her Ph.D. research, Yamamoto and her colleagues embedded CNT networks in aerospace composites. During their mechanical testing, both the CNT networks and the composites broke. This caused the local electrical and thermal conductivity to change as defects formed. By applying a small current, the defect locations would heat

Image Credit: Bigstock



A zoomed-in image from a scanning electron microscope showing details of shear banding behavior of a nano-porous anodic aluminum oxide membrane. Credit: Jingyao Dai

up and could be simply detected using a thermal camera.

Other applications

Yamamoto speculated on other uses for oriented nanoparticles: “It would be cool to apply our knowledge to biomedical applications, like to deliver drugs or to break blood clots. The magnetic assembly method is non-contact, and we can control particle locations, density, speeds, and so forth.”

Recently, Yamamoto has been thinking about the possibility of using magnetic assembly in 3D printing. “Currently, particles and fibers in the ink are organized by the printer nozzle’s movement. If we could incorporate a magnetic field into the printer nozzle, we could organize them separately from the nozzle movement.”

About Prof. Yamamoto

Namiko Yamamoto left Japan as a teenager to come to school in the U.S.

“It takes a lot of energy and guts to study abroad, so you might as well do it when you’re young,” she says. “Living in a foreign country definitely made me grow a lot as a person. It has not been an easy journey, but I have been extremely lucky with friends, teachers, and colleagues.

“I wanted to come to the U.S. because I wanted to be an astronaut. I didn’t realize that I couldn’t apply for an American astronaut slot, because I am Japanese. It shows how much a 17-year-old knows about the world,” she laughs.

At MIT, she chose aerospace engineering over astrophysics as her major, because she realized that her interest is in making things rather than in observing far-off phenomena.

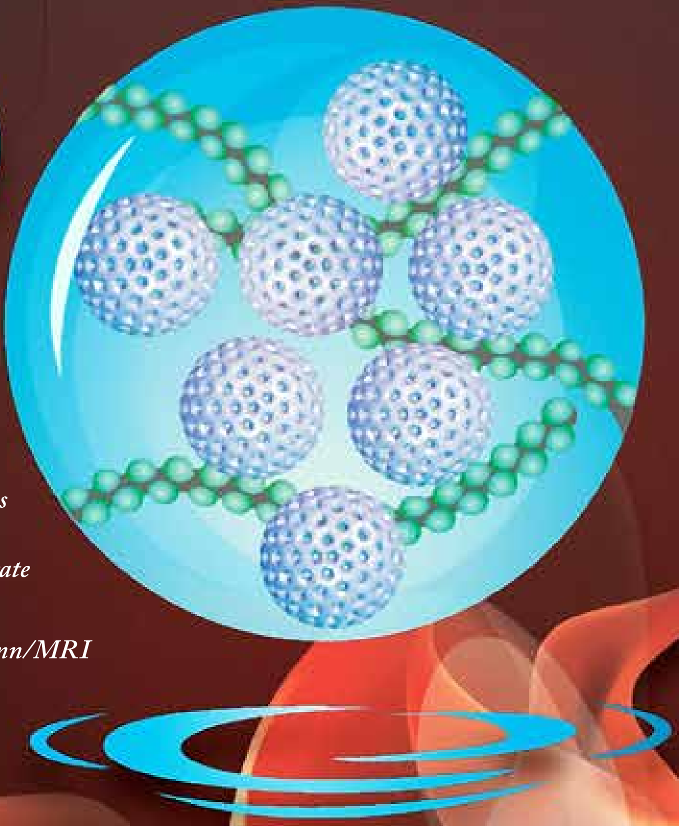
Yamamoto is the principal investigator for the Advanced Composites and Engineered Materials Group and an assistant professor of aerospace engineering. She received her B.S., M.S., and Ph.D. in Aeronautics and Astronautics from MIT. Her post-doctoral training was at Caltech and NASA’s Jet Propulsion Lab. She joined the Penn State faculty in July 2014.

Contact Prof. Yamamoto at nuy12@psu.edu.

A NEW PROCESS FOR SINTERING CERAMICS AT LOW TEMPERATURES

Could Save Money and Cut CO^2 Emissions

A new technology developed by Penn State researchers, called Cold Sintering Process (CSP), has opened a window on the ability to combine incompatible materials, such as ceramics and plastics, into new, useful compound materials, and to lower the energy cost of many types of manufacturing.



An artistic interpretation of the cold sintering of ceramic particles (white) and polymer strands (green) using low heat to evaporate added water molecules (blue).

Illustration: Jennifer M. McCann/MRI

Prof. Randall with former lab member Dr. Seth Berbano (left) and undergraduate researcher Kris Verlinde discuss a ceramic sample. Credit: MRI

"In this day and age, when we have to be incredibly conscious of the CO^2 budget, the energy budget, rethinking many of our manufacturing processes, including ceramics, becomes absolutely vital," said Clive Randall, professor of materials science and engineering at Penn State who developed the process with his team. "Not only is CSP a low temperature process (room temperature up to 200 degrees Celsius), but we are also densifying some materials to over 95 percent of their theoretical density in 15 minutes. We can now make a ceramic faster than you can bake a pizza, and at lower temperatures."

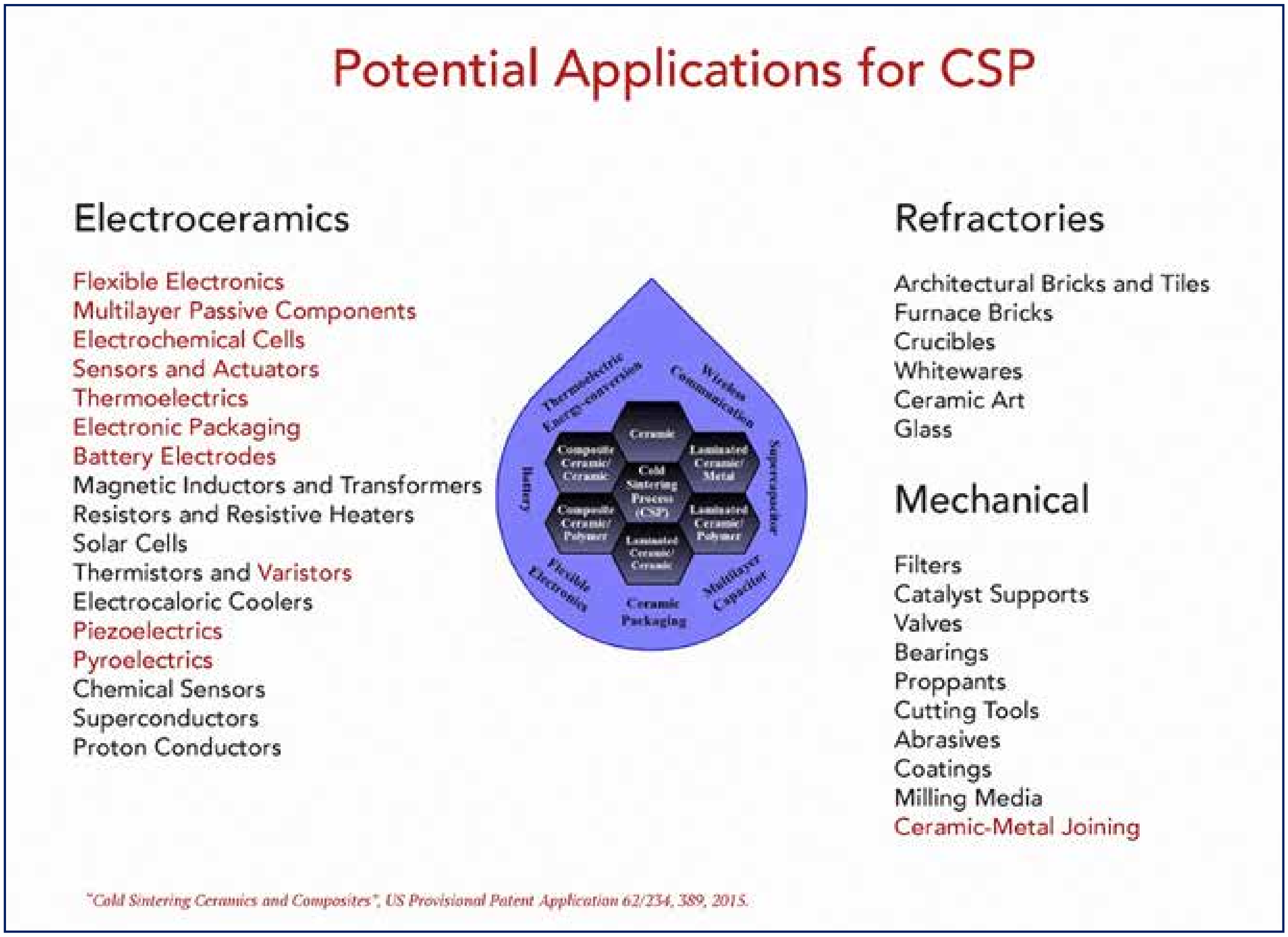
The making of ceramics using heat is the oldest of manmade materials processes, dating back tens of thousands of years. Ceramic products are found in every corner of the Earth and even in orbit, from table settings to the tiles used on the space shuttle to protect it from the heat of re-entry. What once was the stuff of grain storage casks and clay figurines is now the highly engineered material used in semiconductor electronics, biomedical implants, and jet engines.

The common denominator of all these manmade ceramic objects is heat, very high heat. Penn State professor of engineering science and mechanics Michael Lanagan points out, "There is a long trend in reducing the process temperature in ceramics. The dream is to get ceramics to consolidate at much lower temperatures. Then all sorts of things open up."

Within the space of a year, the Randall group has shown that the long-sought process of consolidating, also called sintering, ceramics at low temperature has been achieved. In around a dozen peer-reviewed articles published in 2016 and early 2017, the researchers described the process of sintering ceramics at room temperature up to around 200 degrees C, far below the normal temperatures of 1000 degrees C and above. As of early 2017, Randall's team has successfully sintered over 50 composite systems using CSP.

Just add water

According to the researchers, the process involves wetting ceramic powder with a few drops of water or acid solution. The solid surfaces of the particles decompose and partially dissolve in the water to produce a liquid phase at particle-particle interfaces. Adding temperature and pressure causes the water to flow and the solid particles to rearrange in an initial densification process. Then in a second process, clusters of atoms or ions move away from where the particles are in contact,



Potential Applications for CSP

Electroceramics

Flexible Electronics
Multilayer Passive Components
Electrochemical Cells
Sensors and Actuators
Thermoelectrics
Electronic Packaging
Battery Electrodes
Magnetic Inductors and Transformers
Resistors and Resistive Heaters
Solar Cells
Thermistors and Varistors
Electrocaloric Coolers
Piezoelectrics
Pyroelectrics
Chemical Sensors
Superconductors
Proton Conductors

Refractories

Architectural Bricks and Tiles
Furnace Bricks
Crucibles
Whitewares
Ceramic Art
Glass

Mechanical

Filters
Catalyst Supports
Valves
Bearings
Proppants
Cutting Tools
Abrasives
Coatings
Milling Media
Ceramic-Metal Joining

"Cold Sintering Ceramics and Composites", US Provisional Patent Application 62/234, 389, 2015.

which aids diffusion, which then minimizes surface free energy, allowing the particles to pack tightly together. The key is knowing the exact combination of moisture, pressure, heat, and time required to capture the reaction rates so the material fully crystallizes and gets to very high density.

"I see cold sintering process as a continuum of different challenges," Randall says. "In some systems, it's so easy you don't need pressure. In others you do. In some you need to use nanoparticles. In others, you can get away with a mixture of nanoparticles and larger particles. It really all depends on the systems and chemistries you are talking about."

The Penn State team has begun building a library of the precise techniques required to use CSP on various materials systems, with 50 processes verified to-date. These include ceramic-ceramic composites, ceramic-nanoparticle composites, ceramic-metals, as well as ceramic-polymers.

Other areas that are now open to exploration by CSP include architectural materials, such as ceramic bricks, thermal insulation, biomedical implants, and many types of electronic components.

Why is sintering at low temperatures so important?

There have been hints of this low-temperature sintering capability before, Lanagan says. Penn State is well known for its work in chemically bonded ceramics and has a long history in ceramics processing. "Like anything in science and technology, you build on things you've learned from others. In my mind, that is the root of this discovery."

Having so much prior knowledge of ceramics, the team is able to follow a set of chemical guidelines to

understand the possibilities for CSP. "We know all these materials really well," Lanagan says. "We know where their applications are, and now we are starting to make them through the cold sintering process."

Ceramics are produced in high-temperature ovens that gobble up electricity, much of it produced by coal, gas, and oil combustion, adding substantially to the burden of greenhouse gases in the atmosphere. Cement, which is produced at high temperatures, is alone responsible for around 5 percent of global CO^2 emissions. It is entirely possible that cold sintering process could be used in the manufacturing of cement, and a group in Zurich, Switzerland, is already experimenting with CSP for this purpose.

Reducing CO^2 is of global importance, but reducing the cost of manufacturing ceramics and composites is what makes business people pay attention. Energy is expensive, and reducing the time and temperature required to produce a densified product in an energy intensive manufacturing process could strongly impact a company's bottom line.

Richard Clark, senior technical specialist for Morgan Advanced Materials, an international company that is building a Center of Excellence at Penn State, speculated that the savings in energy costs could be worth billions to industry, if the process could be ramped up to factory floor scale.

"I still have some skepticism," he said. "Will there be problems with scaling up? Is there a reason it wasn't discovered 50 or 100 years ago? Will we replace a floor of high temperature furnaces with a similar number of hot press machines? But if this is the real thing, it could mean billions, or more likely tens of billions, in value."

CO^2 reduction and cost savings are both highly commendable outcomes of low temperature sintering, but from a curiosity driven perspective, CSP opens up a dizzying array of possibilities for new material composites — composites that could never be sintered in a single process because their temperature requirements were incompatible.

In November 2016, The Department of Energy's ARPA-E program announced a $1 million award to Penn State researchers to develop safe and reliable polymer-ceramic composites for next generation battery and fuel cells using the cold sintering process. Associate professor of chemical engineering Enrique Gomez is the lead PI on the project. "This project leverages a new approach to processing ceramics that has been recently developed by the Randall group at Penn State," Gomez said in a press release.

In a 2016 article in the journal *Advanced Functional Materials*, Randall and his coauthors described the co-sintering of ceramic and thermoplastic polymer composites using CSP. Three types of polymer were selected to complement the properties of three types of ceramics, a microwave dielectric, an electrolyte, and a semiconductor, in order to highlight the diversity of applicable materials. These composite materials demonstrate new possibilities for dielectric property design, and both ionic and electronic electrical conductivity design. These composites can be sintered to high density at 120 degrees C in a timeframe of 15 to 60 minutes.

Other areas that are now open to exploration by CSP include architectural materials, such as ceramic bricks, thermal insulation, biomedical implants and many types of electronic components.

"My hope is that a lot of the manufacturing processes that already exist will be able to use this process, and we can learn from polymer manufacturing practices," Randall concluded.

Along with Randall and Lanagan, postdoctoral scholars Jing Guo and Hanzheng Guo, and research and development engineer Amanda Baker are part of the team developing the patent-pending technology.

Their work is supported by the National Science Foundation as part of the Center for Dielectrics and Piezoelectrics and the NSF-ERC ASSIST program, the 3M Science and Technology Fellowship, and the Department of Energy GATE Fellowship.

Contact Prof. Clive Randall at car4@psu.edu.

NEW DIRECTIONS IN ADDITIVE MANUFACTURING

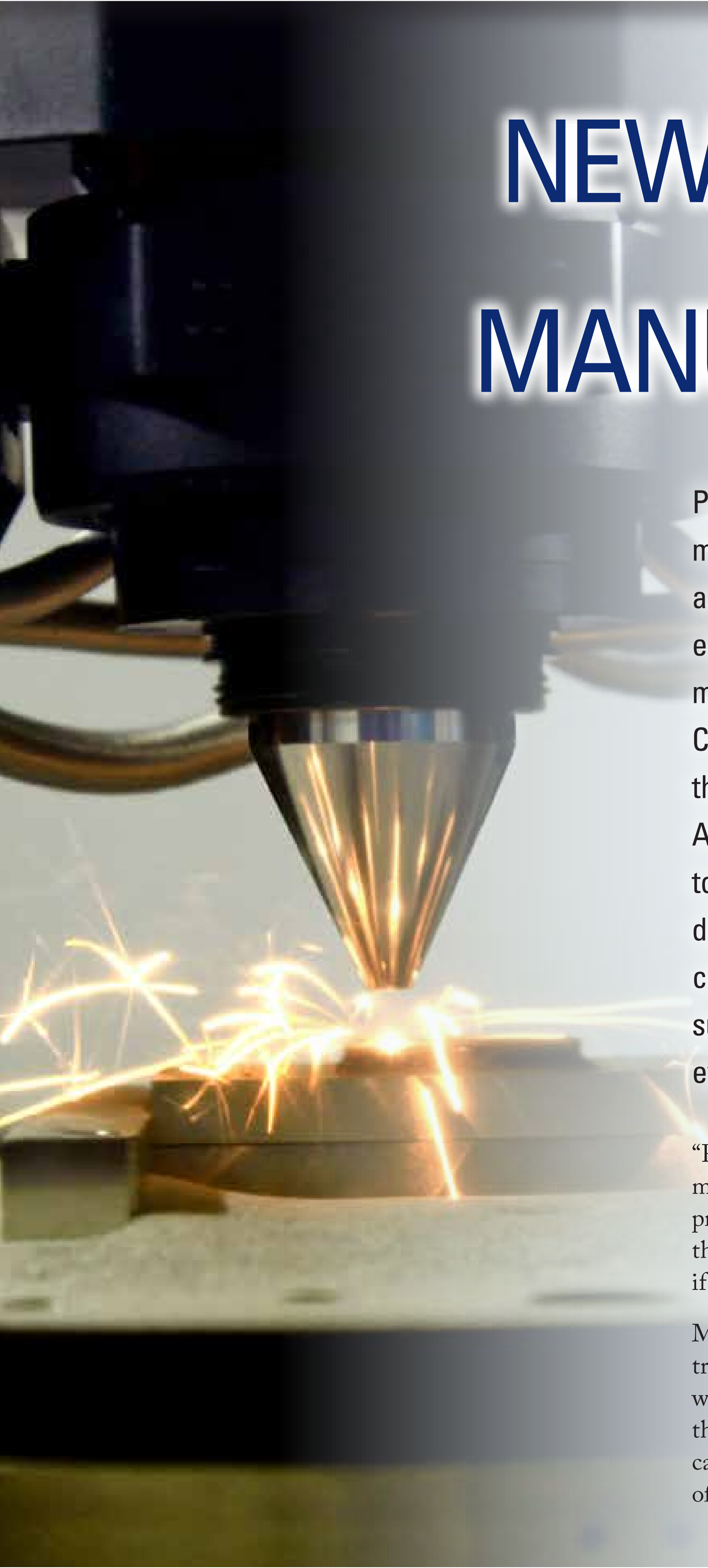


Image Credit: Bigstock

Penn State has a strong history in traditional manufacturing techniques, such as casting and machining. Now Penn State has emerged as a leading U.S. center in additive manufacturing (AM) expertise through the Center for Innovative Materials Processing through Direct Digital Deposition (CIMP-3D). Additive manufacturing, commonly referred to as 3D printing, uses three-dimensional digital models to produce structures of varying complexity one layer at a time from materials such as metals, plastics, ceramics, glass, and even biological tissue.

“Penn State is really good at both additive and traditional manufacturing,” says Guha Manogharan, assistant professor of mechanical engineering. “CIMP-3D is the focal point for additive manufacturing nationally, if not worldwide.”

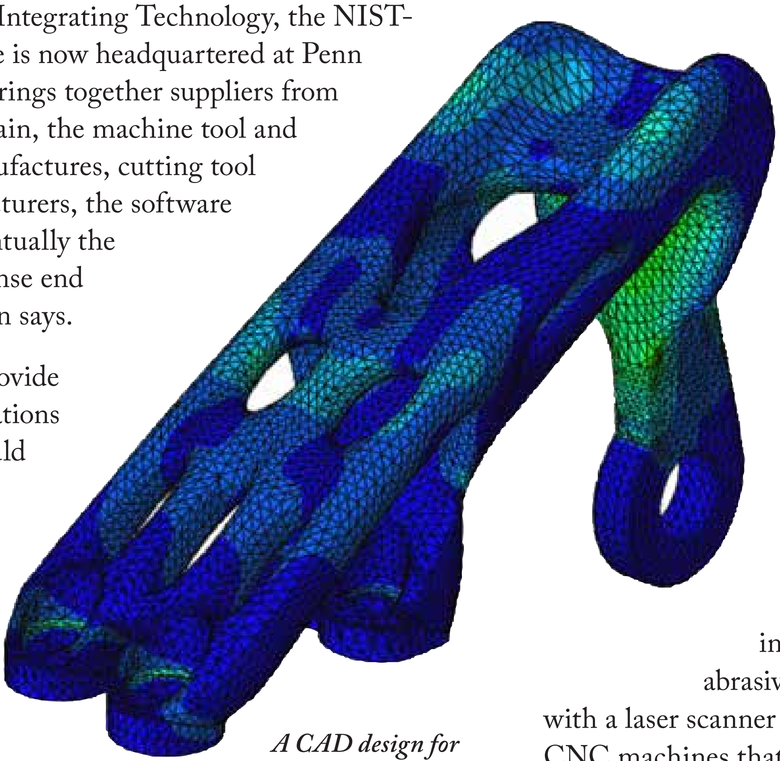
Manogharan has a background in both additive and traditional manufacturing technologies, and his current work involves bridging the technologies to bring some of the subtractive technologies, such as machining, and the casting technologies, such as sand casting, into the field of additive manufacturing.

Guha Manogharan in the CIMP-3D laboratory. Credit: Penn State

He leads a national consortium charged with developing a technological roadmap for integrating the additive processes with traditional manufacturing processes. Called CAM-IT, which stands for Consortium for Advanced Hybrid Manufacturing—Integrating Technology, the NIST-sponsored initiative is now headquartered at Penn State. "CAM-IT brings together suppliers from across the value chain, the machine tool and AM machine manufactures, cutting tool and CNC manufacturers, the software providers, and eventually the aerospace and defense end users," Manogharan says.

Industry leaders provide the types of applications for which they would like to use AM, but are currently unable to use it for, and university researchers will address the technological issues and what is needed to overcome them. Now in its final stage, the consortium is moving from road mapping into a research project phase based on industry inputs, which ranks applications vs. time-line vs. technological priorities.

Within Penn State, Manogharan leads the SHAPE (Systems for Hybrid-Additive Process Engineering) lab, which includes a new metal additive hybrid system that integrates AM and direct digital subtractive manufacturing operations in both a single machine and across different machine envelopes. The lab is located in the CIMP-3D space in Penn State's Innovation Park.



A CAD design for 3D sand printing Credit: Jiayi Wang

The purpose of hybrid manufacturing is to overcome some of the limitations of AM that are often overlooked in the excitement of the new technology, according to Manogharan. These challenges include achieving a high precision tolerance, a smooth surface, and uniform directional mechanical properties. The latter problem, which is affected by the build direction of 3D printing, can strongly affect the strength and reliability of parts and will likely require intensive modeling, heat-treatment studies, and nondestructive testing to resolve. But hybrid technologies can solve the high precision and smooth surface challenges that need to be overcome in order to make parts that can fit seamlessly into a jet engine or automobile chassis.

One of Manogharan's major research efforts is the design and development of a hybrid system that incorporates machining, abrasive flow polishing, and grinding with a laser scanner in a series of multi-axis CNC machines that seamlessly integrate AM and post-processing to get the best of both technologies.

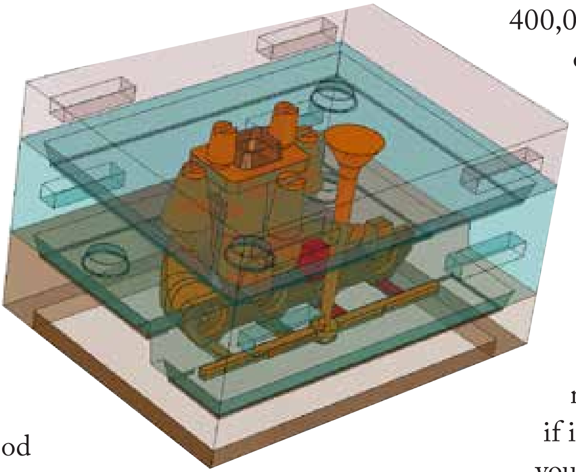
"Our research group is focusing on developing both digital and advanced processing tools for hybrid manufacturing that would greatly enhance both the traditional and growing AM value chains," he says.

3D Sand Printing

With funding from America Makes, Manogharan is combining one of the oldest methods of manufacturing, known as sand casting, with one of the newest methods, additive manufacturing. He calls this new combined process 3D sand printing.

"Penn State has always had a very good casting program," he says. "We recently got a grant based on how we can combine two completely different areas of manufacturing in metal casting and 3D printing."

Sand casting is a little like making a sand castle. Wetted sand is packed around a pattern made out of a material such as wood or plastic, much like ice trays are used to make ice in the shape of the tray. The pattern is removed and molten metal is poured through a hole in the top into the core, where it takes the shape of the part. When the metal cools, the sand is broken away to retrieve the cast part. It is estimated that 70 percent of all metal castings per year are produced via sand casting. The number of parts produced by metal casting is huge, including the engine blocks of all the cars on the road.



3D sand printing design of a turbo-exhaust manifold reduces weight by over 20 percent. Credit: Santosh Reddy Sama

In 3D sand printing, the molds and cores for metal casting are printed directly on layers of sand in a powder bed process that deposits an adhesive binder onto layers of sand until an entire mold is fabricated.

"With 3D sand printing, you spread a layer of sand and deposit glue as a binder in the spaces you want. Keep doing it until you have every layer of the box except where you have the shape you want for the metal to be poured into," he explains.

In traditional sand casting, the pattern has to be removed before the metal is poured, which limits the shape of the mold. With 3D sand printing, almost any complex shape is possible, and consolidation of cores makes it even more economical.

"We did a project with an auto manufacturer in Detroit working on redesigning the engine block and the manifold," Manogharan says. "We were able to reduce the weight by 20 percent, which may not sound like much. But on a truck designed to run for 400,000 miles, that adds up to a lot of fuel saved."

3D Custom Orthopedic Implants

"My father was in a bike accident and had to get a shoulder implant. When you buy a shirt or coat, you typically only have a choice of small, medium, large, extra-large. But if it is a very important ceremony, you might go to a tailor and have it custom made. Shouldn't we do that for something that's going into our body?" Manogharan wonders.

To answer the question, he has begun working with Penn State's Milton S. Hershey Medical Center on 3D printing of shoulder and knee implants. This is an area he believes is especially suitable for 3D printing because it fits three important criteria for 3D: complex design, customizability, and low cost. Their collaboration was recently awarded a grant to design and develop 3D printed metal implants for pediatric oncology studies.

"The U.S. is far behind in this area, which is mostly due to regulations. My goal for the next three-to-five years is to reach out to colleagues with a range of biomedical and clinical expertise in order for us to be the leading university to develop 3D printed custom metal implants for patients," Manogharan concludes.

Prof. Manogharan is an active member of ASME, IISE and SME and was named the 2016 Outstanding Young Investigator by the IISE— Manufacturing and Design Division and the 2017 Outstanding Manufacturing Engineer by the SME— Society of Manufacturing Engineers.

Contact Prof. Manogharan at gum53@psu.edu.

FAST–

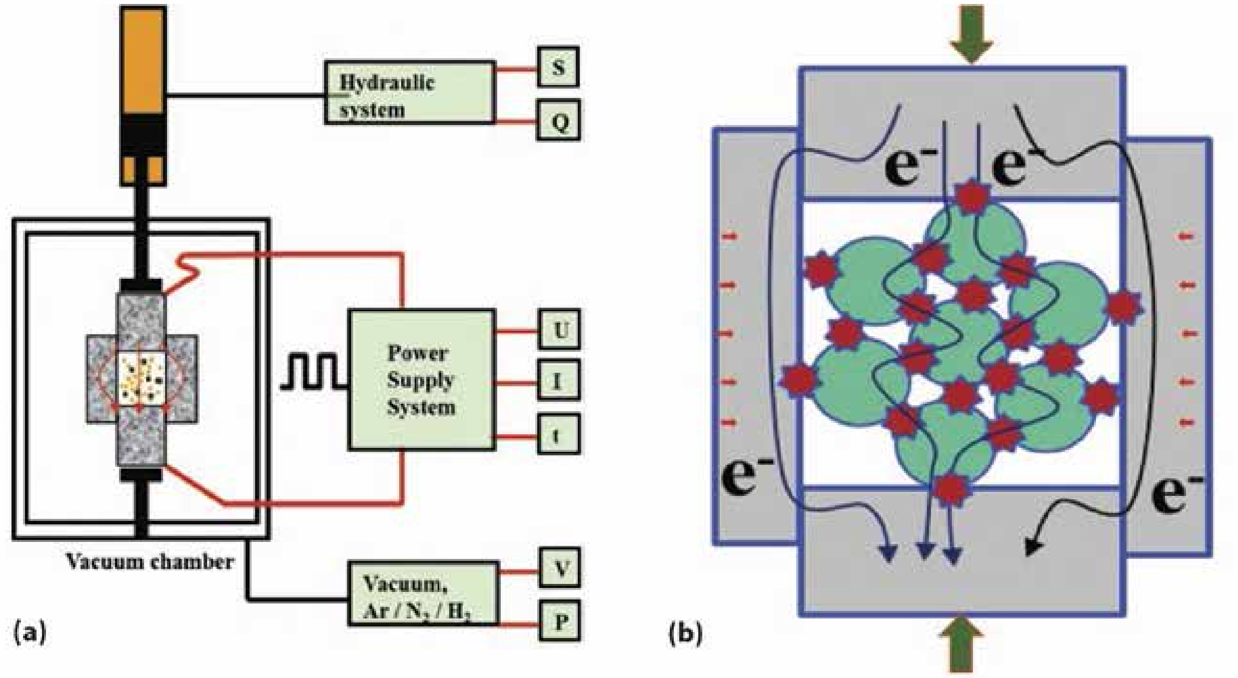
PENN STATE'S MANUFACTURING-SCALE FAST SINTERING TECHNOLOGY

Sintering is the process of turning a powder material into a net-shaped component, that is, one that is close to its final shape, using heat and pressure. A new type of sintering, called Field Assisted Sintering Technology (FAST), uses a pulsed or continuous high density electric current delivered through the pressure mold and the powder to cause very rapid heating and dramatically shorter sintering times. The process can achieve new materials compositions and properties that could not previously be obtained.

The Penn State Applied Research Laboratory (ARL) has acquired three FAST units, likely the most of any academic institution in the country, according to Jogender Singh, senior scientist in ARL and professor of materials science and engineering, who oversees the FAST machines and center of excellence. "I started the program in 2008, with a very small R & D unit with a 25-ton capacity," Singh says.

As the value of the technology became apparent, Singh was able to obtain a larger unit with a 250-ton capacity. Later, with a grant from the Navy, he bought a 320-ton capacity hybrid machine that allows him to sinter parts up to 350 millimeters in diameter.

"The purpose of such a large machine is to let industry come and make a sub-scale or full-scale part and see if the technology is right for them before buying their own expensive machine," he says. On a tour of the facility, which is part of the Applied Research Lab but located off campus, the industrial scope of the equipment was obvious. The hybrid unit is so large that it needed to be lowered by crane through a large hole cut in the roof. It stands two stories high.



(a) Schematic diagram of field assisted sintering technology/spark plasma sintering technology and (b) materials interaction with mold.

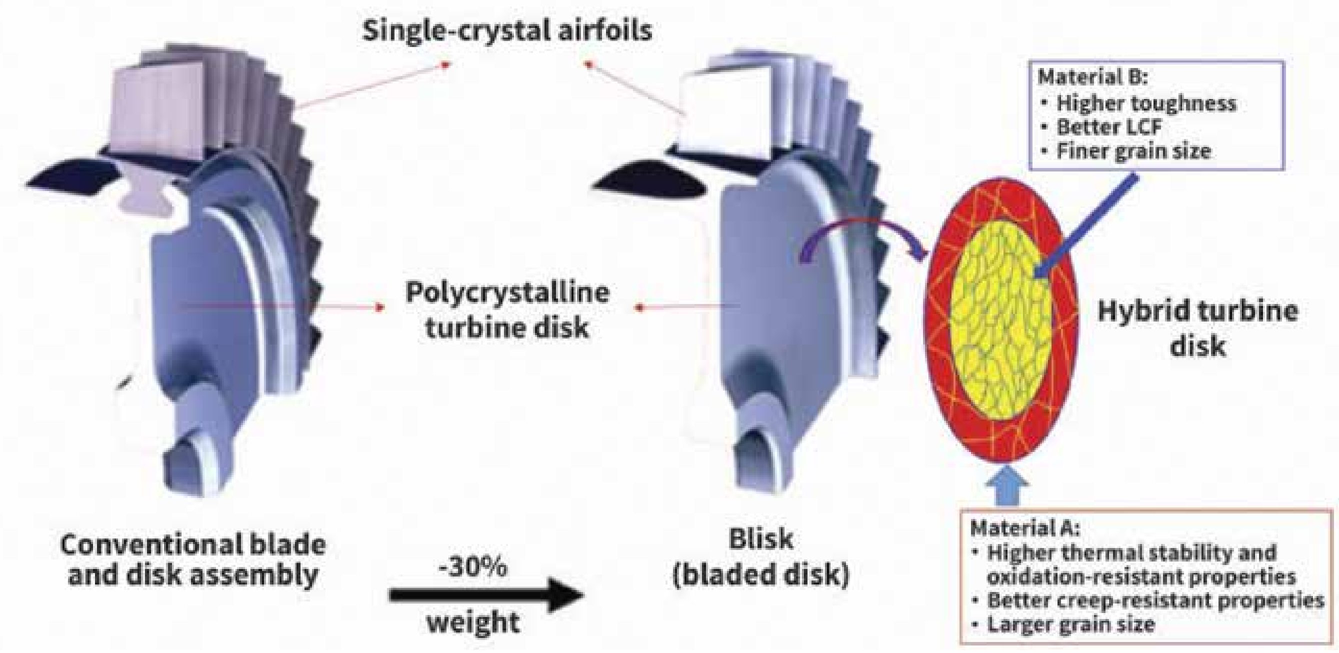
Kennemetal, a powder-metal company based in Western Pennsylvania, was an early funder of his research. When he was able to demonstrate to them that the technology was capable of producing parts with good mechanical properties, they purchased a production unit for their UK branch and had Singh continue with R&D at Penn State. “The technology has been validated by the Navy and Department of Defense and directly transferred into manufacturing,” he says.

FAST could be considered a fusion of two prior technologies — arc welding and high current density diffusion bond welding. Developed and widely used in Japan since the early 1990s, the technology has now spread to Europe and the U.S. Singh convinced the Department of Defense to bring the technology to ARL-Penn State, which is now the leader in FAST R&D in the U.S.

Singh has funding from NASA to develop a prototype hybrid rocket nozzle/thruster, which is being tested for a potential Mars mission. NASA wants thrusters with twice the thrust-to-weight ratio of current components. To reach that goal the Penn State researchers are using FAST to sinter components with extraordinary thermal conductivity, good mechanical properties and light weight. For the Army, Singh is using the technology to make cheaper, lighter body armor composed of ceramic tiles.

“This technology is very effective at making body armor ceramic tiles cost effectively,” he says. “In addition, this allows us to make custom body armor for female soldiers cost effectively and in a very short time.” The process involves digitally scanning the soldier, creating a graphite mold via CNC machining, and sintering boron carbide powder into customized plates.

“We have developed a novel concept for making ceramic tiles with a new architecture,” he adds.



Bladed-disk (blisk) structure offers significantly reduced weight compared with a conventional blade and disk assembly.

Singh was recently funded by the Army Research Lab to work on hybrid turbine disks. Aerospace engines with gas turbines can be made with lighter, stronger and faster rotating components to increase thrust using FAST.

“This is a revolutionary concept that allows us to make hybrid turbine disks that will allow the aerospace industries to operate the engine at a much higher thrust,” Singh says. “This will lead to lower fuel consumption, higher speed, and better performance.”

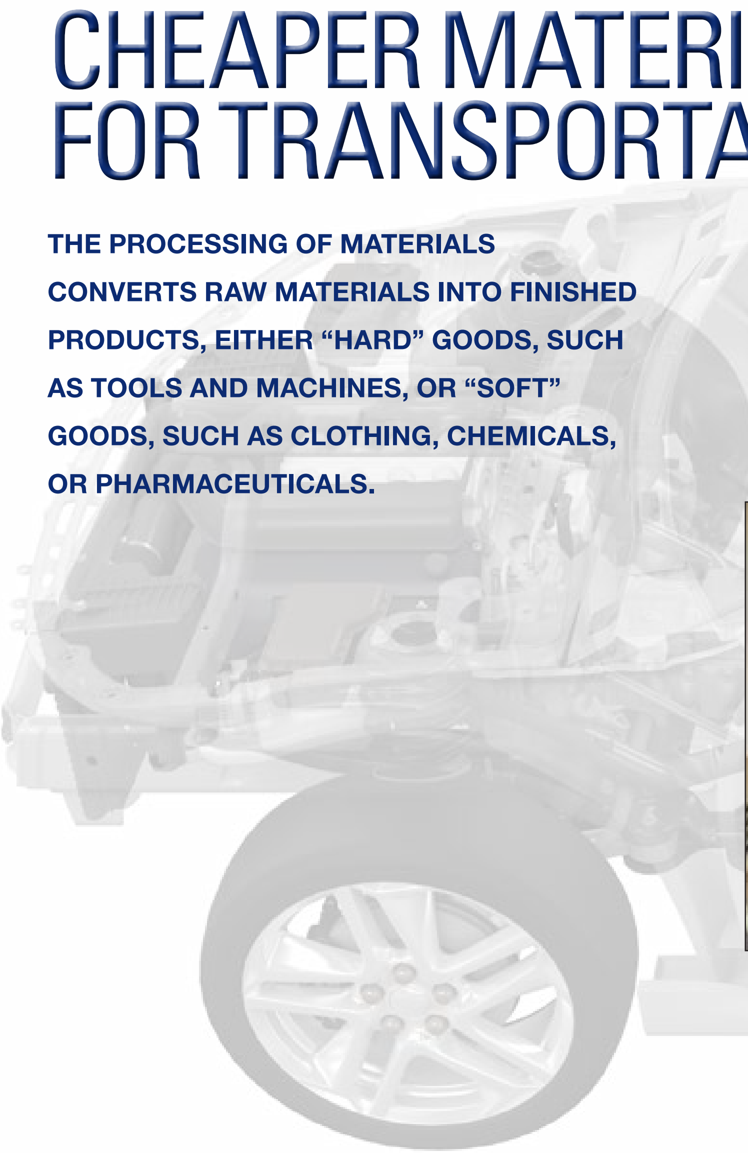
NASA has developed a low-density, single-crystal, nickel-based super alloy for turbine blades. However, normal methods of joining components could result in catastrophic failure of the parts due to micro-cracks, residual stress, and large grain size. With FAST technology, the ARL team joined the components with perfect bonding at the interfaces.

FAST has also been used to make highly reflective silicon carbide disks from powder materials for lightweight optics for space applications.

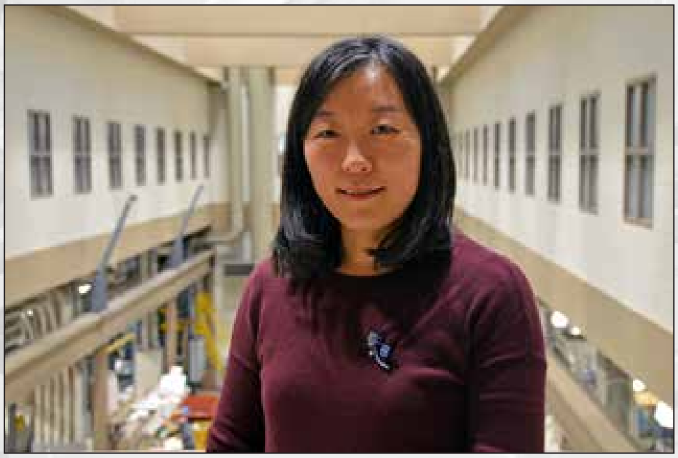
“Every material behaves differently under high pressure and high temperature conditions. So, we have to tailor our processing window for a given material and given net-shaped component. We have experts who design the molds for each component, and those designs are a challenge we are overcoming every day. It’s a team effort involving design engineers, technicians, students, and industry,” Singh concludes.

To learn more about Field Assisted Sintering Technology contact Prof. Jogender Singh at jxs46@psu.edu.

THE MOVE TO LIGHTER, STRONGER, CHEAPER MATERIALS FOR TRANSPORTATION



THE PROCESSING OF MATERIALS CONVERTS RAW MATERIALS INTO FINISHED PRODUCTS, EITHER “HARD” GOODS, SUCH AS TOOLS AND MACHINES, OR “SOFT” GOODS, SUCH AS CLOTHING, CHEMICALS, OR PHARMACEUTICALS.



Jinjing Li, associate professor of industrial and manufacturing engineering, overlooking the Factory for Advanced Manufacturing Education (FAME Lab) in the Leonhard Building. Credit: MRI

Materials processing is as old as civilization, but since the beginnings of the Industrial Revolution manufacturing technology has gone through three distinct phases. The first phase was mechanical mass production, including the assembly line, standardization of parts, and the invention of new machines. Mass production is still dominant, but toward the middle of the twentieth century, an electronics revolution began with the invention of the transistor. This phase is characterized by Moore’s Law, which for 50 years reflected the multiplication of speed and the reduction in cost of computing. The current phase is cyber/digital, which is anything related to computer-aided design (CAD) and information sharing, according to Jingjing Li, an associate professor of industrial and manufacturing engineering. Li came to Penn State in 2016 from the University of Hawaii in Manoa.

“People have different views of advanced manufacturing because they have different backgrounds and because

Image Credit: Bigstock

funding announcements use different terms for advanced manufacturing," she says. "Some call it Smart Manufacturing, which is mostly at the systems level. Or they call it Digital Manufacturing, because they believe everything will have a digital component, which is at both the systems level — how things are organized — and the process level — how things are made. But the revolution is here: software, hardware, automation, and production on a systems level."

Her research is primarily concerned with how things are made — the tools and methods of manufacturing — with a particular interest in methods such as advanced welding techniques used to join the new materials that are being introduced into the automotive and aerospace industries.

When traditional bonding techniques won't work

Advanced manufacturing can require the bonding of incompatible materials. Li is an expert in new techniques that can bond materials when traditional bonding doesn't work.

"My research is in lightweighting — how to make a car lighter by using advanced materials such as aluminum, magnesium, or carbon fiber composites", she explains. "The benefits of such advanced materials lie in their high strength-to-weight ratio, which makes it possible to reduce the vehicle's weight and thus reduce greenhouse gas emissions."

But traditional bonding won't work with dissimilar materials that have different melting temperatures. If the materials can't fuse, or if they form an intermetallic compound that is brittle or prone to fracture, other bonding methods are required. One such method is called friction stir welding.

"There are two types of welding," says Li, "fusion, which is what most people are familiar with in welding shops and garages across America, and solid state welding, which doesn't melt the metal. The latter doesn't apply any external heat source; friction alone heats the metal to a plastic state. For instance, aluminum is a softer metal than steel and the friction stir technique works well to bind aluminum and steel together."

Invented in Great Britain in the early years of this century, friction stir uses robots to apply a spinning metal pin at the juncture of two materials, which then soften and bond along a weld.

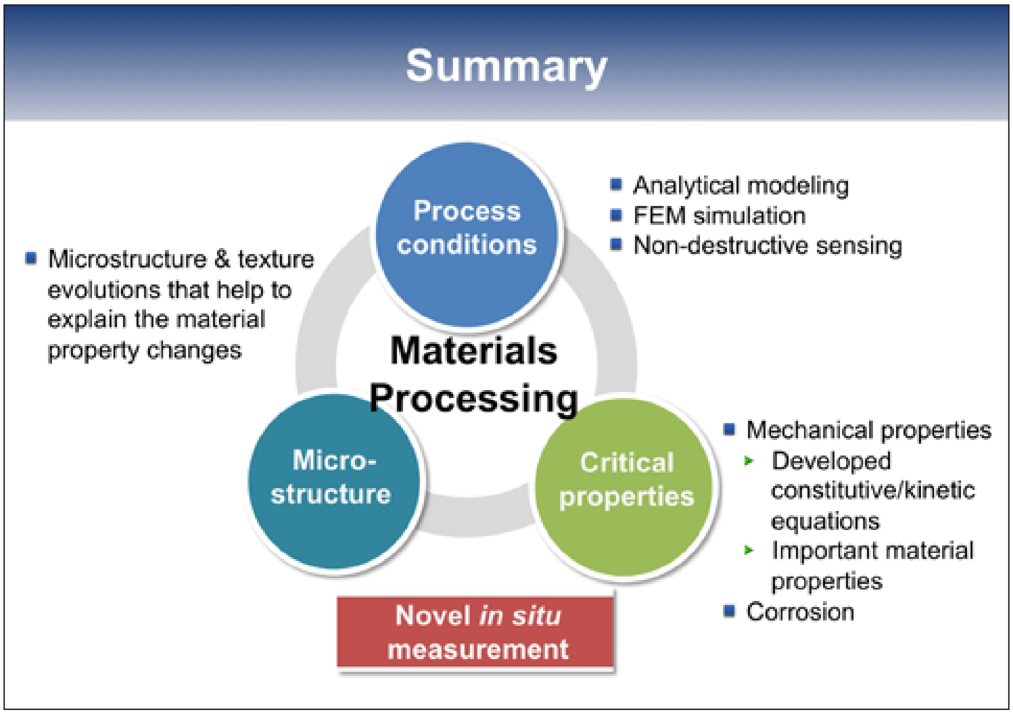
Li uses a somewhat similar technique, patented by General Motors, that is a combination of friction stir and mechanical riveting. Called friction stir riveting, the technique drives a rivet into friction-softened materials. Once the rivet is locked, the rivet binds the materials.

"In future, researchers are also looking to friction stir to bond higher strength steels," she says. "We've been talking with Zi-Kui Liu (Penn State professor of materials science and engineering) about simulating friction stir to get a better idea of what is happening in the bond formation."

Lightweighting is important in the automobile and aerospace industry, both of which are driven to reduce fuel consumption without losing the strength of traditional heavier materials. Boeing's 787 Dreamliner, for example, uses advanced composites, which account for 50 percent of the airplane's total weight. Along with allowing for a lighter structure, the composite materials are better at resisting impacts, easier to repair, and do not fatigue or corrode.

In the automotive realm, a 10 percent reduction in vehicle weight can reduce fuel usage by 6-8 percent. The DOE's Vehicle Technologies Office says that replacing cast iron and traditional steel components with high-strength steel, magnesium alloys, aluminum alloys, carbon fiber, and polymer composites can reduce the weight of a vehicle's body and chassis by up to 50 percent. Lightweight materials are particularly important for hybrid and electric vehicles, as they could lead to smaller and less expensive batteries and greater driving range.

Another area of Li's research is the characterization of composites used in the automotive industry, supported by the Ford Motor Company. Using X-ray computed tomography (CT), which combines multiple X-ray images into a three-dimensional image, she studies and characterizes the microstructure of advanced composite



Summary

- Microstructure & texture evolutions that help to explain the material property changes

Process conditions

- Analytical modeling
- FEM simulation
- Non-destructive sensing

Materials Processing

Micro-structure

Critical properties

- Mechanical properties
  - Developed constitutive/kinetic equations
  - Important material properties
- Corrosion

Novel *in situ* measurement

Credit: Jingjing Li

materials. The microstructure of composites varies with changes in processing and can have important impacts in the materials' performance.

"We use the Materials Characterization Lab quite a bit," she remarks. "The transmission electron microscopes and the scanning electron microscopes and sample preparation. We've invited the MCL researchers to come over here (Leonhard Building) to give short talks on the various techniques they have in the Millennium Science Complex, X-ray diffraction, etc. In summary, my research involves materials characterization and mechanical behavior."

Li was an assistant professor in Hawaii for five years prior to coming to Penn State. In that time, she received the National Science Foundation Faculty Early Career Award, a prestigious award for outstanding research by junior faculty. Her work on joining of dissimilar metals was rewarded with a $500,000 grant. Li received her bachelor's degree in materials science and engineering from Beihang University in Beijing, China; a master's degree in materials science and engineering from Tsinghua University in Beijing; and a master's degree in statistics and a Ph.D. in mechanical engineering from the University of Michigan in Ann Arbor.

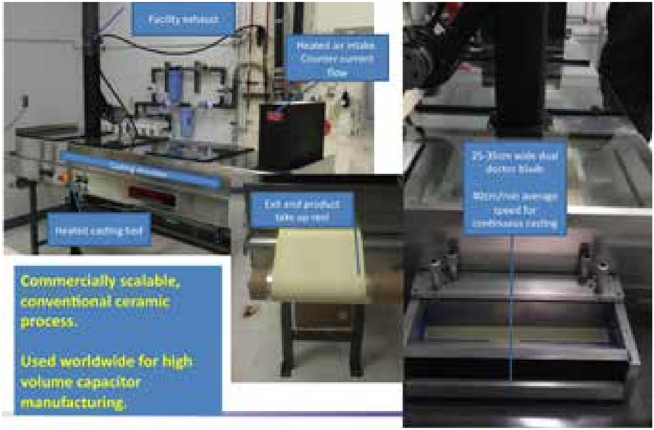
"I feel like sometimes materials scientists focus more on fundamental science and frequently don't talk to industrial engineers. I can fill some gaps between them because of my materials science and mechanical engineering background," she remarks.

"For instance, I believe I can connect those two areas to make things more practical, because while materials scientists want to publish in high impact journals, it takes a long time to translate those findings into reality. But manufacturing is tied to industry, and so we can bring our research into the real world much sooner."

Jingjing Li is the William and Wendy Korb Early Career Professor of Industrial and Manufacturing Engineering. Contact her at jul572@psu.edu.

TEXTURED CERAMICS:

FROM LAB EXPERIMENTS TO A VIABLE TECHNOLOGY



Pilot-scale laboratory equipment for textured ceramic manufacturing Credit: ARL

Most discoveries born in the university laboratory never make it into the marketplace. They may add to the sum total of scientific knowledge, but the road from idea to product is a long and torturous one. That has certainly been the case with Penn State's research on textured ceramics, which the Messing lab has worked on since the late nineties. But recently, with the help of the Navy and Penn State Applied Research Lab, the road ahead has become much more promising.

Ceramics have multitudinous uses, but the Navy's interest is mainly in underwater sonar. Both sonar and medical ultrasound use a property of certain types of material called piezoelectricity. When an electric voltage is applied to these ceramic materials, the result is a small mechanical transformation. Conversely, when mechanical pressure is applied, the result is a small electrical response. This piezoelectric effect is used in a variety of sensors, energy harvesters, ultrasonic cleaning and welding, as well as the aforementioned sonar and ultrasound.

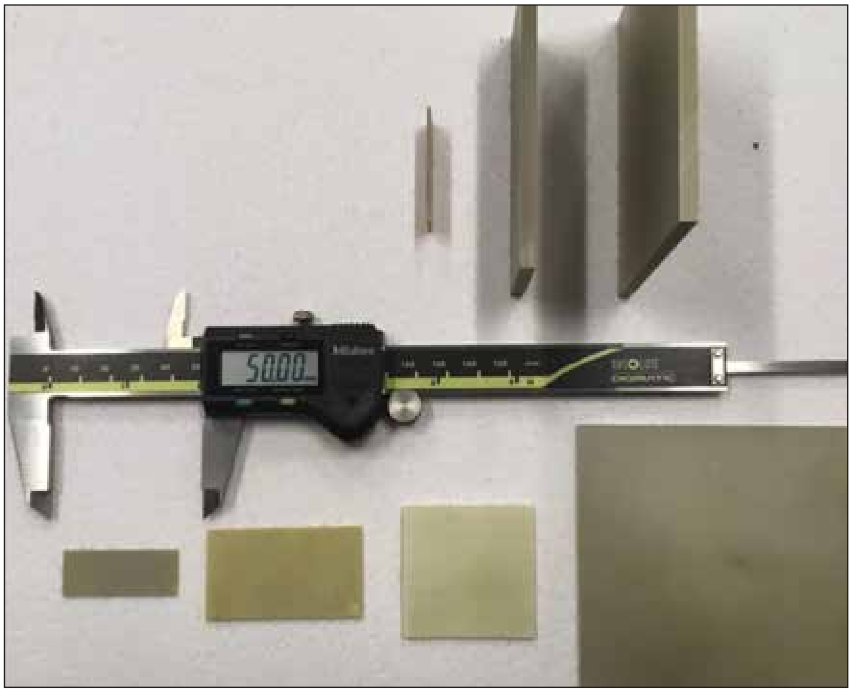
"It is especially useful anytime you are sensing what's under the ocean," says Gary Messing, Distinguished Professor of Materials Science and Engineering at Penn State and the lead author of a recent review article in the *Journal of Materials Research* describing a number of advantages of ceramics with piezoelectric and other properties and new ways to make them. "We are talking about mineral discovery, oil and gas discovery, deep well monitoring, and energy harvesting."

Messing's lab has been developing an intriguing approach to making high-performance ceramics for these applications, called texture engineering. By texture, he is not referring to patterns on the surface of the ceramic, but rather engineering the crystal orientation throughout the material. The properties of a ceramic are determined by two things: the intrinsic crystal arrangement of the material and the microstructure. In polycrystalline ceramics made from powder, the arrangement of crystals is random and the piezoelectric response is relatively low. At the opposite end of response are single crystals, which are essentially one grain aligned in one direction.

For some applications, polycrystalline ceramics are sufficient. They are cheaper and more robust than single crystal ceramics. But there is great interest in improving on polycrystalline performance, if the cost and robustness can be retained. Enter textured ceramics.

"That's the reason anyone would even consider going in this direction," Messing explains. "There are key

Image Credit: Bigstock



Examples of textured ceramics in various sizes and conformations Credit: ARL

advantages of making a material that falls between single crystal and polycrystalline ceramics, with performance close to single crystal performance. For one, it is much easier and less expensive to make large parts. To make a large part from single crystals, you need to tile smaller pieces together. Very expensive. Our method of textured growth uses tape casting, which is a standard industry process."

Textured ceramics use a process called templated grain growth. Small crystal particles are oriented in a particle matrix and when the mixture is heated, the particles tend to induce the rest of the mixture to grow in a single direction. The result is very similar to the uniformity of single crystal.

In the lab, thin strips or tapes of the ceramic mixture are stacked on top of one another by hand, typically by a graduate student, and then heated to induce the grain growth. The process is tedious, even to make small samples for testing.

The Applied Research Lab scales up the process

Richard Meyer is an associate professor of materials science and engineering and a senior scientist at the Penn State Applied Research Lab (ARL). Meyer has studied the properties of single crystals in detail for his work with the Navy.

Messing says, "We had been working in the area of textured ceramics for a long time with funding from the Navy. Then, for whatever reason, the funding went away and the work slowed down. Then Dr. Meyer came along."

"We needed to take it out of the lab," Meyer says, "and into the hands of the people who can do something with it."

Messing and Meyer made some pieces of the textured ceramic in the lab that had good performance in a Navy transducer (the heart of the sonar device), and the Navy asked the Applied Research Lab to do the research on the processing requirements to take this material to the pilot-scale production level, Meyer says. "Our niche is being able to produce parts that are outside the form factor and beyond the quantity that are viable in single crystal."

In their facilities in Freeport, Pennsylvania, 30 miles northeast of Pittsburgh, a group led by Dr. Mark Fanton is spearheading the effort to produce quantities of high

quality textured ceramics capable of being handed off to manufacturers for potential device production on an industrial scale.

"This material is approaching single crystal performance," Meyer says, "and we are getting closer every day. We've gone to great lengths to scale the processing conditions from grams to kilograms."

With funding from the Defense University Instrumentation Program (DURIP), the Freeport facility has purchased a system that automates the stacking and lamination process. "With this machine, you program the shape you want and it will stack and make parts 24/7," Meyer says.

Messing adds, "That's why the Freeport operation is so important. Typically, the customer is buying 10-100 parts so they can put it in their transducer design. There is no way in an academic environment that we could ever upscale to that."

In the process of scaling up to manufacturing level, a constant feedback loop has developed between Freeport and the Meyer and Messing labs at University Park. "What we are learning on the scaling side leads back to the lab. But also, what they are learning on the lab scale is leading back to improve the pilot-scale program," Meyer remarks.

They are working with a number of perovskite ceramics, including lead indium niobate, lead magnesium niobate, lead titanate, collectively known as PIN-PMN-PT. A key advantage to the textured ceramic process is the ability to maintain chemical homogeneity in the multicomponent single-phase ceramic, something that is near impossible to achieve in growth of large single crystals. This is a key advantage of texture-engineered ceramics, because properties such as piezoelectricity are highly sensitive to chemical composition.

The next step

The goal of the program, says Meyer, is to simultaneously create both supply and demand. This requires getting the material to the point where they can hand it off to industry to build devices and evaluate performance.

"We have enough data to know there is interest. It's just a matter of getting the material and processing information into the hands of the vendors," he says.

Penn State has an open door policy when it comes to industry. If companies want to see the process in action, they are welcome to come to either the Freeport facility or to Penn State's University Park campus. "They can tap our resources to facilitate adoption of this technology to the commercial side," Meyer says.

In the review article in the *Journal of Materials Research*, Messing and Meyer, along with their collaborators, shared the technology with the research community in order to extend the oriented ceramics technique beyond piezoelectrics.

"The other part of this story is that there is opportunity to make other kinds of property sets by making textured materials, including mechanical, thermal, electrical, and ion conducting materials," Messing. "There are many applications for this approach, both including piezoelectrics and beyond."

Original article: "Texture-engineered ceramics — Property enhancements through crystallographic tailoring" DOI: 10.1557/jmr.2017.207

Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author and do not necessarily reflect the views of the Office of Naval Research that sponsored some of this work.

Contacts: Gary Messing at messing@ems.psu.edu or Richard Meyer at rjm150@arl.psu.edu

FACULTY SPOTLIGHT

Lauren Zarzar

In the Midst of Change

Lauren Zarzar in the newly renovated Steidle Building, home to the Department of Materials Science and Engineering Credit: MRI

by Krista Weidner

The Greek philosopher Heraclitus is quoted as saying, "Change is the only constant in life." That constant change is what motivates materials scientist Lauren Zarzar in her research.

"The world around us is always changing—materials are constantly being exposed to different external pressures, external stimuli," says Zarzar, assistant professor of materials science and engineering and assistant professor of chemistry. "Many materials we use are static in their properties and functions, but I'm interested in designing materials that respond to changes in the environment."

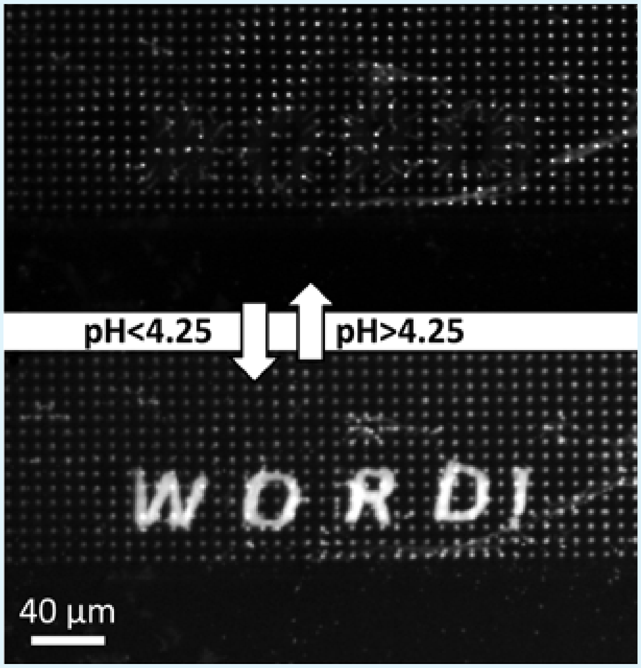
Zarzar received her Ph.D. in chemistry from Harvard in 2013 and joins Penn State after completing her postdoctoral work at MIT, where she focused her research on dynamic materials that sense and adapt to their surroundings—in particular, microscale materials that move in response to a stimulus such as a change in temperature, pH, or humidity.

3D printing on a micro scale

One of Zarzar's major research focuses at Penn State is direct laser writing of metals and oxides to create patterns on a micro scale. "Direct writing, similar to additive manufacturing or 3D printing, lets you pattern a material in whatever shape you want and deposit it directly where you want it, with no need for a mold or mask," Zarzar says. "Although this technique has been gaining popularity, there hasn't been as much work in depositing inorganic materials, such as metals, on a micro scale."

When Zarzar began thinking about using laser lithography to deposit metals, she was interested in using platinum because platinum is a catalyst—a substance that increases the rate of a chemical reaction but doesn't itself undergo a permanent chemical change. She had the idea to create a three-dimensional active structure (a pump, in this case) by causing platinum to interact with a hydrogen peroxide solution. "When I started wondering what chemistry I would use to deposit platinum using light from a laser, I read some of the literature on photography," she says. "And I came upon information about platinum-type photography. It's fairly common knowledge that silver was used to make photographs in the 1800s, but I was surprised to learn it was also done with gold as well as platinum. So as early as the 1800s the chemistry had been developed to make photographs with platinum nanoparticles. It was exciting to be able to demonstrate that we can use this chemistry in direct material deposition with laser lithography."

In initial experiments, when Zarzar deposited the platinum with a light-induced process, she noticed that when the laser light hit the platinum, the surrounding solution would heat up quickly, allowing her to induce new reactions. Next steps in her research will involve exploring a thermal approach in the direct depositing



This image shows a dynamic optical response—an appearing and disappearing image. The word "word" is a gel that expands and contracts in response to changes in pH level. "We are diluting and concentrating a fluorescent dye and that's how it becomes visible and invisible. It's similar to how an octopus changes color," Zarzar says, explaining that an octopus uses chromatophores, or sacs of pigment dye in its skin, that expand and contract to cover its body with different colors and patterns. "We sometimes call this bio-inspired materials design—taking lessons from nature and applying it to new situations."

process as well as depositing materials other than platinum. Direct depositing of metals and oxides has potential applications for direct-write circuits, sensors, catalysts, and electrodes.

Drop by drop

Zarzar's second major research focus is looking at how emulsions of different fluids interact with chemicals in their environment. She creates complex droplets that include two different immiscible oils—or oils that don't form a homogeneous mixture when they're added together—and changes the droplets' shape by adding various chemicals to the solution. "By adding chemicals like a surfactant, such as soap," she says, "we can change how the droplets respond to a range of stimuli."

Emulsification, Zarzar explains, is a well-known and powerful technique for mixing and dispersing components through liquid, and emulsions are critical components of many medicines and foods. Complex emulsion properties and functions are related to the droplet structure and are becoming increasingly important in pharmaceuticals and medical diagnostics, cosmetics, and optics.

Zarzar credits her graduate research advisor at Harvard, Joanna Aizenberg, for sparking her interest in responsive and adaptive materials. "I started working on projects in this area as a new graduate student in her group, and I was immediately fascinated," she says. "It's exciting work, and it's fun—you get to take movies when you study active materials."

For Zarzar, research can be approached in different ways. "Sometimes, I have a definite idea and I know what materials I'm going to use and what I want to accomplish from the onset," she says. "Other times I see something interesting or unusual along the way and go back to figure it out and delve into it more deeply."

Beyond research

Zarzar and her husband moved to the State College area from Cambridge during the summer, and she began her position with Penn State on August 1, 2016. Her husband, whom she met at Harvard during graduate school, is a lecturer in the Department of Chemistry and involved in developing chemistry courses for Penn State World Campus. "Penn State was a good fit for both of us," she says.

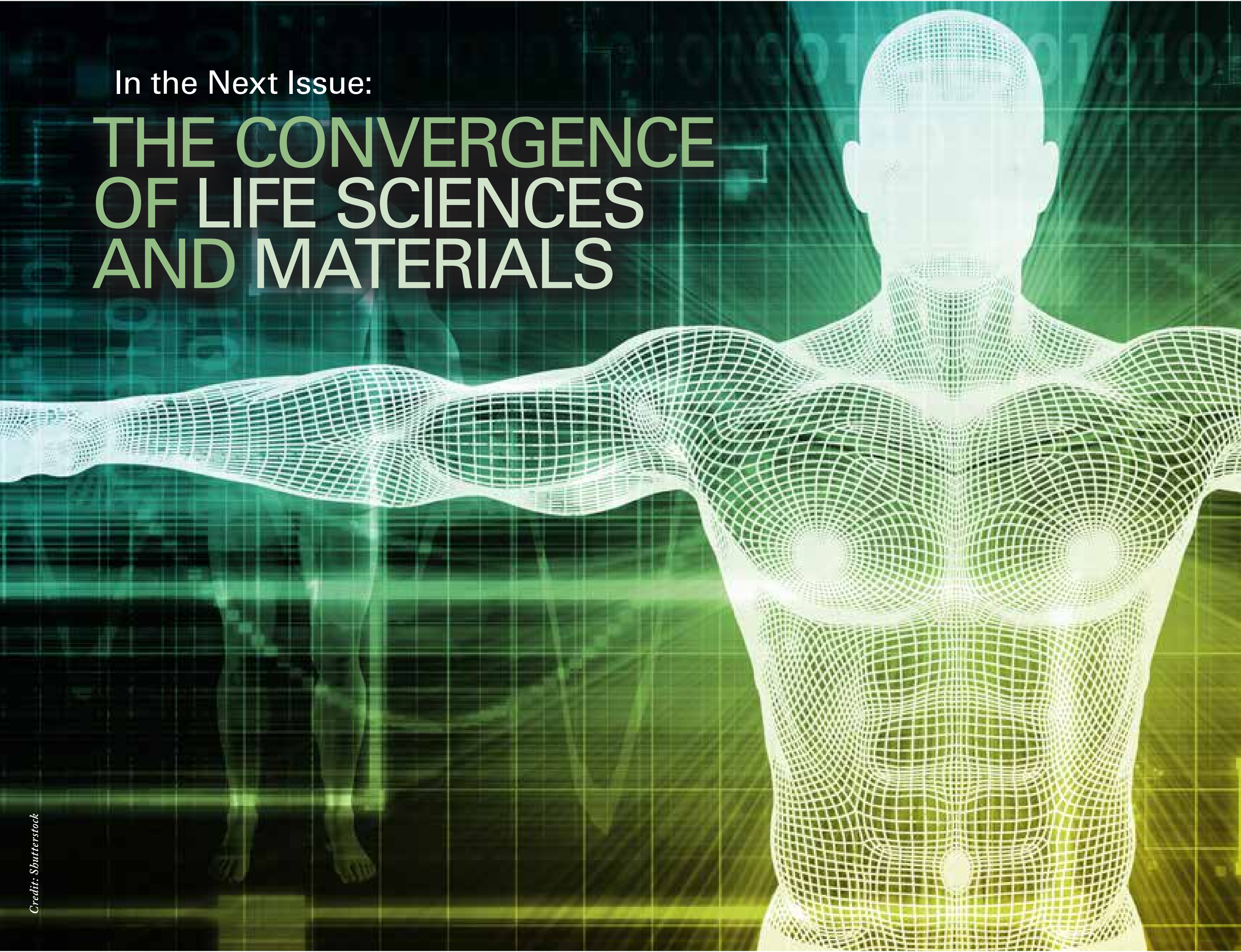
During fall semester, Zarzar set up her lab and trained two graduate students and one undergraduate. She'll begin teaching the undergraduate course Introduction to Polymer Materials during spring semester. She was recently named the Virginia S. and Philip L. Walker Jr. Faculty Fellow in Materials Science and Engineering. In addition, she is an assistant professor of chemistry.

Contact Prof. Zarzar at dz4@psu.edu.

Materials Research Institute
The Pennsylvania State University
MRI N-317
Millennium Science Complex
University Park, PA 16802

PennState

Nonprofit Org.
U.S. Postage
PAID
State College, PA
Permit No.1



In the Next Issue:

THE CONVERGENCE OF LIFE SCIENCES AND MATERIALS

Credit: Shutterstock