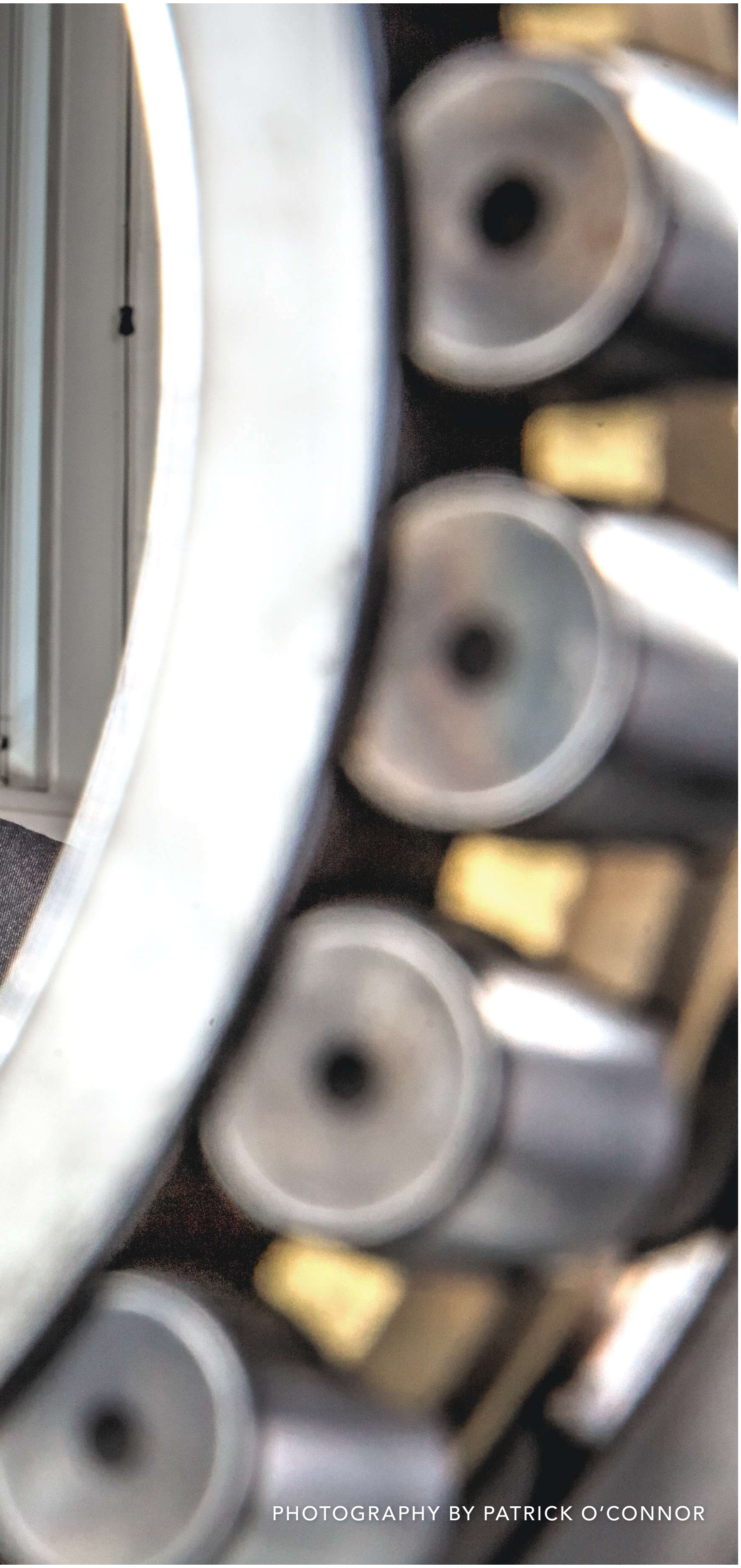
Surrounded by a traditionally cast metal part, Diran Apelian, director of WPI's Metal Processing Institute, holds an intricate metal object made, layer by layer, using additive manufacturing.


PHOTOGRAPHY BY PATRICK O’CONNOR

IT ALL ADDS UP

BY ALEXANDER GELFAND

The next frontier in manufacturing is making metal parts, layer by layer, with 3-D printing. Researchers at WPI are addressing the challenges of additive manufacturing and taking this technology in exciting new directions.

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Additive manufacturing, also known as 3-D printing, is nothing new. Designers in industries ranging from transportation to toy manufacturing use three-dimensional polymer printers to rapidly prototype new products, while hobbyists and researchers have used similar equipment to produce everything from musical instruments to mandibular jaw implants.

But the next step in additive manufacturing will take the technology into a new, more complicated, and far more challenging realm: printing three-dimensional objects with metal. WPI faculty members and students in materials science and engineering are helping define the boundaries of this new frontier as they draw upon their extensive expertise in metals processing, manufacturing, materials characterization, and performance evaluation to help launch what could be the next industrial revolution.

According to **Diran Apelian**, PhD, Alcoa-Howmet Professor of Mechanical Engineering and director of WPI's Metal Processing Institute (MPI), 3-D polymer printers are not unlike common inkjet printers. Instead of depositing liquid ink on paper, they lay down layer upon layer of heated, viscous polymers to build up 3-D objects based on CAD (computer-aided design) files.

Additive manufacturing with metal works in much the same way, except that rather than melting powdered polymers, the highly sophisticated "printers" typically use lasers or electron beams to heat metallic powders or wires to high temperatures, depositing layers of fused metal (see diagram, p. 39). Cold spray, another emerging additive manufacturing technology, accelerates metallic powders to supersonic speeds, causing them to fuse on contact with any substrate in their path.

PLUSES AND MINUSES

Additive manufacturing has a number of benefits. **Diana Lados**, PhD, associate professor of mechanical engineering and director of WPI's Integrative Materials Design Center (iMdc), says the technique can produce parts more quickly and fabricate far more complex geometries than conventional casting and forging methods, all while consuming less energy and generating less waste. And **Richard Sisson**, PhD, George F. Fuller Professor of Mechanical Engineering and director of WPI's Manufacturing and Materials Science and Engineering programs, notes that while large parts that must be produced by the thousands, such as automobile engine blocks, will likely always be made from big forgings, additive manufacturing is a superior method to produce small runs of parts that can be extremely expensive to manufacture by conventional means.

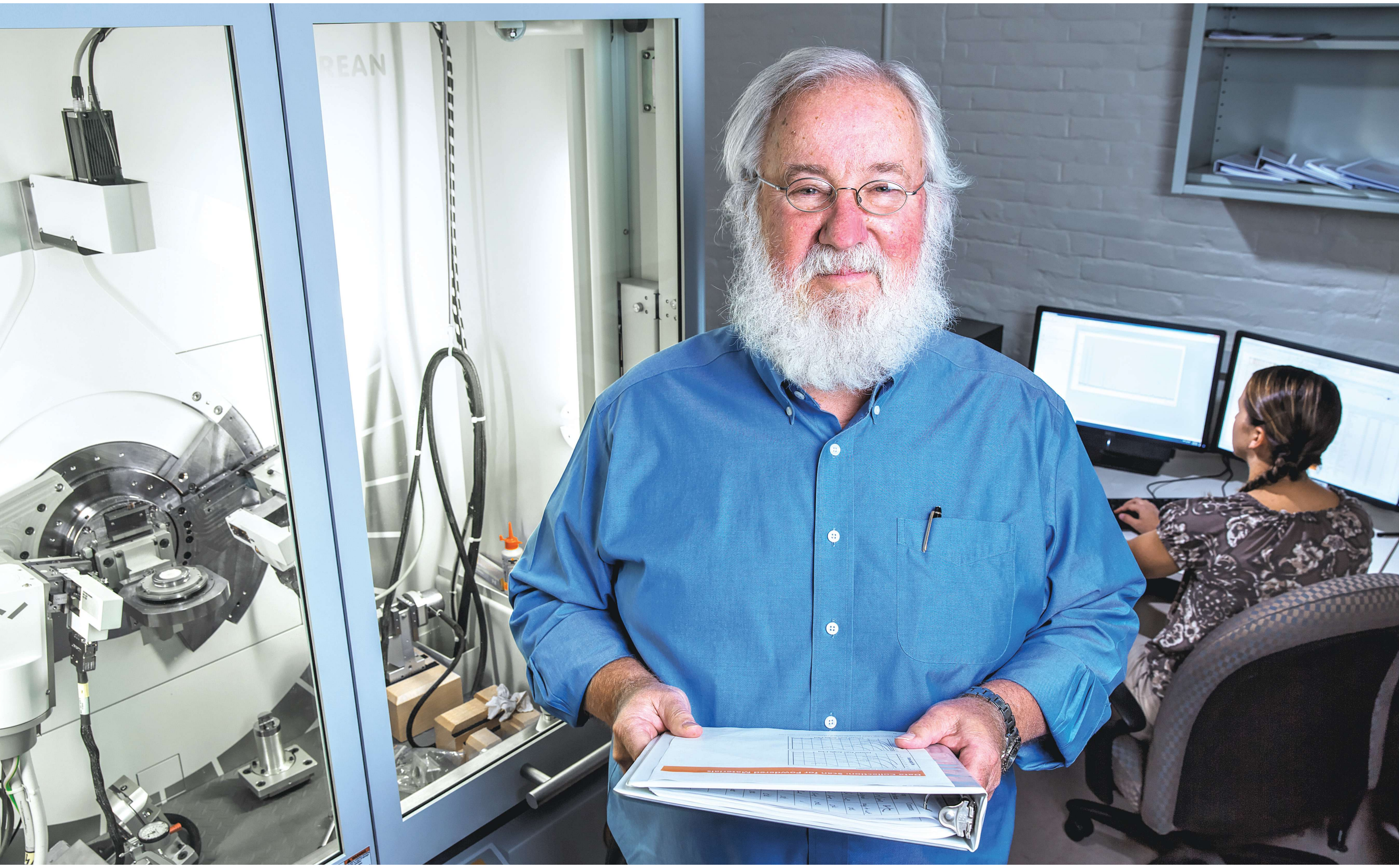
Forging a single replacement part for a jet engine, for example, can take months and cost upwards of $100,000, while simply making the die to cast a transmission case can cost more than a million dollars — a fact that helps explain why so many of the corporations that lend their expertise and support to MPI and iMdc have shown a keen interest in additive manufacturing. The technology also allows for individually customized parts, a feature of considerable interest to the biomedical industry. Imagine, for example,

"The more people understand this technology, the more versatile it becomes." —DIANA LADOS

Diana Lados in the lab where she and her students (clockwise, from left, PhD candidates Joshua Morales, Anthony Spangenberger, and Yuwei Zhai) test additively manufactured parts, like the 3-D printed sample Lados is holding.

a knee or hip implant that can be tailored to a patient's anatomy, rather than chosen from a narrow range of standard sizes, as is the case currently.

But much work remains before additive manufacturing with metals can become commonplace. For one thing, researchers need to better understand the distinctive microstructures they see in parts made by different additive manufacturing processes. They also need to determine how those unique microstructures give rise to different properties, and how those properties affect performance. Only then will they be able to predict how a particular material will behave under specific operating conditions.

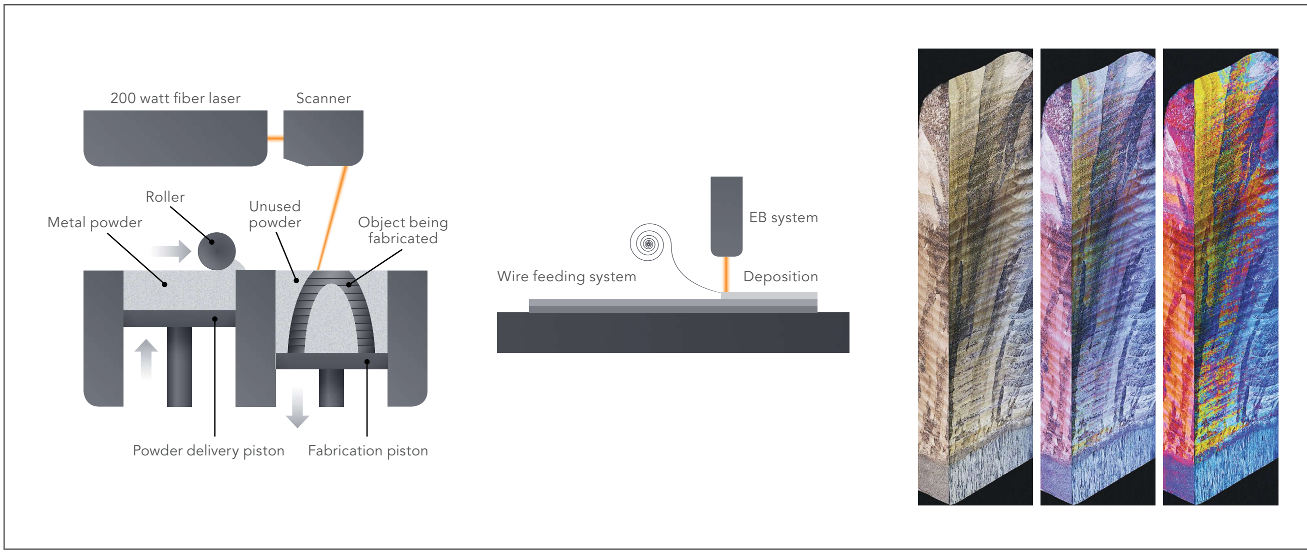


Richard Sisson directs a multi-year project funded by the U.S. Army aimed at understanding and predicting the properties of parts made with cold spray, a "borderline" additive manufacturing tool. With PhD candidate Baillie McNally, he analyzes parts using sophisticated instruments, including this x–ray diffractometer, which can reveal the nanoscale properties of metals by bouncing x-rays off of their surfaces.

THE DEVIL IN THE DETAILS

There's a lot to consider — from the way in which the powder or wire was originally manufactured to the manner in which it is heated and subseqently cooled. And the properties themselves range from strength and ductility to fatigue life to corrosion resistance and porosity, any of which could be important to a specific application. Porosity, for example, is crucial to manufacturing bone implants that can be soaked in antibiotics or used as matrices for growing cells; but without knowing more about how porosity evolves in a specific additive manufacturing process, it's difficult to know exactly how to model and predict it. Add to this the fact that every layer that's laid down affects the ones below it, and you have a very complicated picture.

For the past several years, Rick Sisson has been developing databases and computational models to understand and predict the properties and performance of materials created with cold spray, which he calls a "borderline additive" process because it is currently used primarily to coat and repair existing parts rather than build new ones from scratch. (Funding for his research comes from a multiyear, multimillion dollar agreement with the U.S. Army Research Laboratory, which now commonly uses cold spray to repair magnesium gearboxes in its helicopters and would like to use additive manufacturing to produce entire replacement parts for its vehicles in the field.) But even though 3-D metal printing employs many of the same alloys as cold spray, the fact that they are processed in completely different ways



Additive manufacturing builds up metal parts layer by layer. There are a number of methods that can be used to deposit the layers. In direct metal laser sintering (left), a laser melts layers of powered metal. With electron beam freeform fabrication (middle), a wire is melted using an electron beam. The deposited layers can be seen clearly in the sample at right (from the materials testing lab of Diana Lados) of a titanium-aluminum alloy deposited with laser-engineered net shaping, in which metal powers are melted by a high-powered laser.

means that the parts will behave differently. So Sisson and his colleagues are now undertaking precisely the same work with respect to additive manufacturing processes like powder- and wire-based printing. "Our goal in life is to develop the models to understand the properties, and therefore the performance, of these materials," he says.

UNIQUE WAYS TO FAIL

Diana Lados is working to better understand the unique characteristics and behavior of additively manufactured metal components, especially as the technology makes inroads in high-integrity applications. Since 2011, she and her iMdc collaborators have been developing experimental methods, property databases, and computational tools to help additively manufacture and repair critical structural components for the transportation industry. Among other things, that has meant investigating how various alloys made with additive manufacturing processes fatigue or crack under repeated loading — a phenomenon that Lados has studied extensively in conventionally manufactured and cold-sprayed metal components for the aerospace and automotive industries. (Fatigue is the leading cause of mechanical failure in metals, she says, so understanding how it occurs — and maximizing the resistance of structural materials to it — is vital to the broad implementation of this technology.)

Lados's research has shown that the rapid cooling and reheating of layers as they are deposited during additive manufacturing creates what she calls "micro-heat affected zones" between the layers, which results in non-uniform microstructures and stress distributions. Because of these zones, additively manufactured materials have different properties and failure mechanisms than conventionally manufactured materials.

In other research, Lados is exploring ways to optimize existing laser- and electron beam–based additive manufacturing processes and heat treatments used primarily for titanium and nickel alloys, while also attempting to expand the capabilities of additive manufacturing to a wider range of lightweight structural materials. This includes new studies on additive processing methods for aluminum and magnesium alloys undertaken in collaboration with scientists at Benét Laboratories and Oak Ridge National Laboratory, both iMdc members.

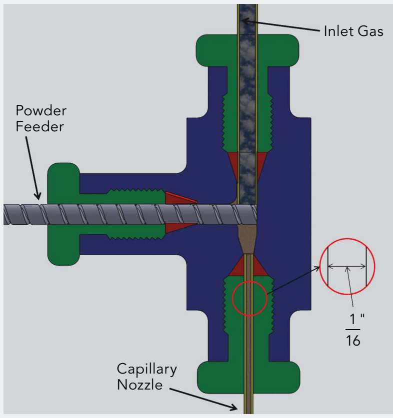
She is also hopeful that additive manufacturing will open up entirely new vistas in materials science; for example, engineers could take advantage of additive manufacturing's unique layering approach to develop new alloys, as well as composite and gradient materials whose composition, microstructures, and properties change across their volume. "The more people understand this technology," she says, "the more versatile it becomes."

DRAWING A FINE LINE

"When people talk about the size limitations of additive manufacturing," says Jianyu Liang, "they are usually referring to the difficulty of using the technology to make really big parts. But there are also limitations in going small."

Liang is working with Ryan Mocadlo '13, a PhD candidate and a U.S. Department of Education GAANN (Graduate Assistance in Areas of National Need) fellow, to develop a new way to use cold spray (the additive manufacturing technology that accelerates metal powders to supersonic speeds to fuse them with a substrate) to make parts at the scale of microns, well below the size of parts typically produced with additive manufacturing.

The key is starting with powders that have particle sizes much smaller than those currently used in cold spray guns, which typically range between 5 and 20 microns. In early work, Liang and Mocadlo have found it difficult to accurately control the feeding of the powders into the supersonic gas stream, resulting in unacceptable variability in the uniformity of the deposited metal. They are currently experimenting with a novel feeding method and trying to learn more about the aerodynamics of the fine metal powders as they speed toward their target.



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A cross-section of a novel cold spray device being developed by Jianyu Liang and Ryan Mocadlo. Extremely small metal powders will be accelerated by gases through the capillary nozzle to produce parts at the scale of microns.

Liang says the U.S. Army Research Laboratory, which is funding her research, is closely following her results. "The Army would like to be able to make very small parts and devices in the field," she says, "so they are very interested in this work."

SMOOTHING ROUGH EDGES

The way additively manufactured parts are processed after they are produced can also affect their properties and their vulnerability to fatigue and cracking, notes **Jianyu Liang**, PhD, associate professor of mechanical engineering. Liang notes that all metal parts, whether made through conventional or additive processes, have rough surfaces that contain burrs or pits that can become initiation points for cracking. Because of the intricate shapes of additively manufactured parts, Liang, whose research expertise includes the nanoscale characterization of materials and electrodeposition, is investigating electrochemical techniques for smoothing and polishing their surfaces. An electrochemical bath will reach even the tiniest nooks that more conventional surface finishing methods like sanding and grinding can't touch. She says she has been engaged in conversations with the Army and Alcoa (which is investing in additive manufacturing) about this approach to surface finishing.

Current techniques for additively manufacturing with metals are not without their limitations. Metallic powder particles, for example, tend to be covered in oxides, and oxides do a great job of initiating the kind of cracks that Lados would like to prevent. Wire-based systems, like the one that Sisson plans to purchase with some of his Army funding, aren't susceptible to that particular flaw, but they do suffer from other problems associated with large cast microstructures and welds. And any method that relies on heating alloys to high temperatures can result in unwanted evaporation.

GOING WITH THE FLOW

Those drawbacks led Apelian to consider an altogether novel approach. Rather than processing wires and powders, both of which are initially manufactured from liquid metal, why not, he asked himself, go back to the source and use liquid metal itself?

Alas, while liquid metal flows well, controlling its viscosity — and the precision with which it is deposited — is no easy task. So in collaboration with researchers at Lawrence Livermore Laboratory and one of the corporate

Jianyu Liang explores electrochemical finishing techniques that can reduce the vulnerability of additively manufactured parts to fatigue and cracking, and uses the scanning electron microscope to observe the effects of those methods. Behind her are, from left, PhD candidates Andelle Kudzal, Yinjie Cen, Yangzi Xu (sitting), and Ryan Mocadlo.

members of MPI, Apelian has turned his attention to thixotropic metals that remain semisolid across a range of temperatures. Pure aluminum, for example, melts at 660 degrees Celsius, whereas an alloy of aluminum and copper might be partially liquid and partially solid from 500 to 750 degrees. The precise temperature within that range determines what fraction of the material is liquid or solid, while the amount of shear applied to it, and the rate at which that shear is applied, controls its viscosity. By manipulating both temperature and shear, therefore, Apelian hopes to achieve the kind of precision required to additively manufacture complex metal components.

There are many ways of improving existing processes, however, and Apelian has more than one iron in the fire. Together with doctoral candidate Aaron Birt, for example, he has been using high-powered lasers to increase the precision of the cold spray deposition process in order to enhance its additive-manufacturing capabilities. And he is also working on a possible collaboration with an MPI member to investigate laser cladding, an additive manufacturing process that can employ either wires or powders.

“There’s not going to be one silver bullet here,” Apelian says. But with this much ammunition, that hardly seems necessary.