OCTOBER 2020 | VOL 178 | NO 7

ADVANCED MATERIALS & PROCESSES

ADDITIVE MANUFACTURING

3D PRINTING AND TRIBOLOGICAL BEHAVIOR OF POLYMER MATRIX COMPOSITES

P. 12

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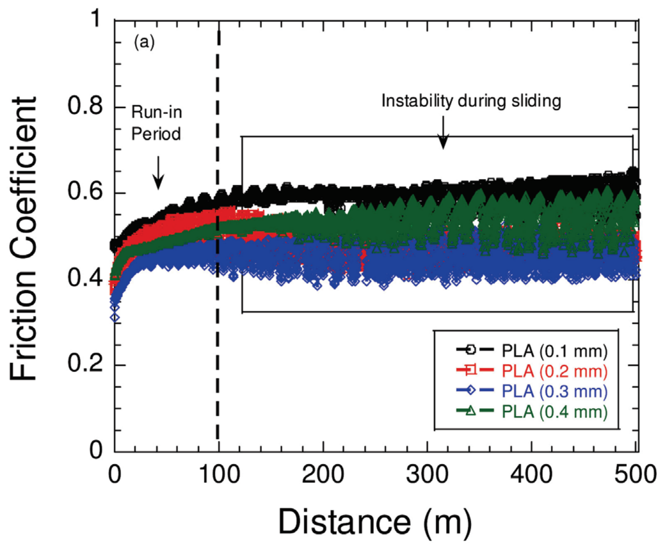
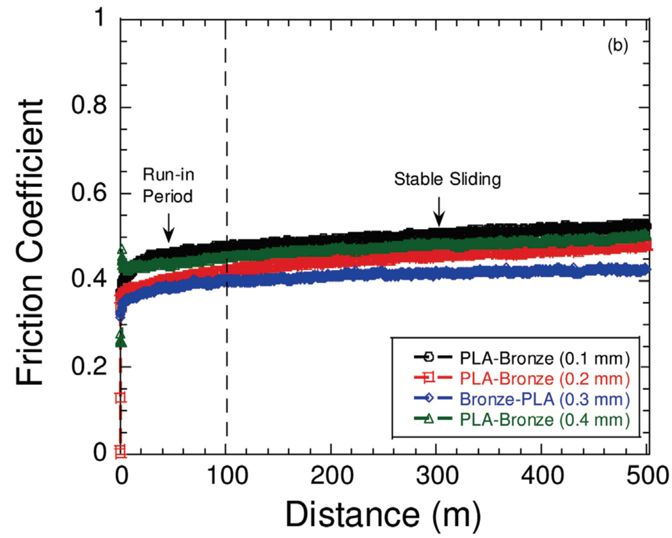
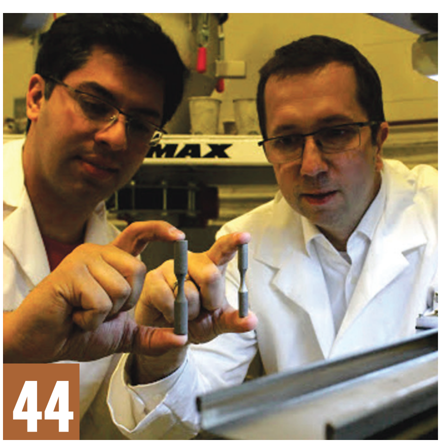
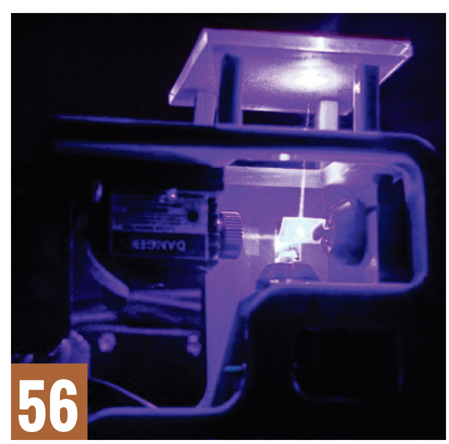




On the Cover:

A 3D-printed shrouded turbine wheel (impeller) for a concentrating-solar-power plant, additively manufactured out of a high-temperature nickel alloy using an advanced VELO3D Sapphire laser powder-bed fusion system. Image courtesy of Hanwha Power Systems.





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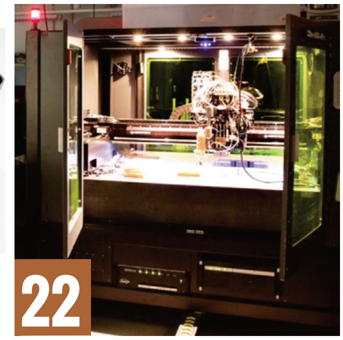

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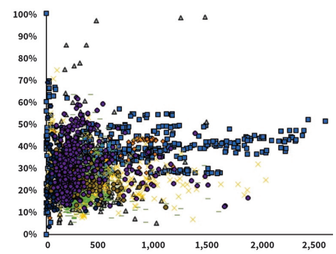

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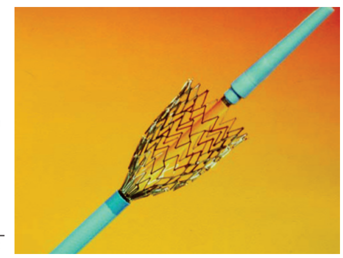

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TRENDS

INDUSTRY NEWS

DEPARTMENTS

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COMMUNITY FIRSTS

For this issue, our Materials Science and Coronavirus series takes us on a short drive from ASM headquarters to Youngstown, Ohio. This is where America Makes—a public-private partnership for advanced manufacturing technology and education—is mobilizing the manufacturing community to address shortages of personal protective equipment, medical devices, and diagnostic test equipment. What an innovative use of community!

Having toured America Makes a few years ago and been enthralled with the candy store-like lobby full of unique 3D-printed objects, it seems fitting to include them in this issue on additive manufacturing (AM). Among this issue's core AM articles, VELO3D shares several case studies showing how the use of metal 3D printing can increase material performance and value.

Our AM coverage continues in the *SMST NewsWire* supplement where we learn how the shape memory alloy (SMA) Nitinol, when 3D printed, can achieve better solid-state cooling performance than that of traditionally manufactured SMAs. By the way, congratulations to the *Shape Memory and Superelasticity* journal on its five-year anniversary. Read the story in the *SMST NewsWire* and learn about the editors to be credited for this success.

The ASM community has more milestones to celebrate. On September 14, during a first-ever virtual ASM Annual Meeting, Diana Essock, FASM, became ASM President and only the third woman to hold the position in the society's history. In place of their "From the President's Desk" and "MD Corner" columns, Essock and Acting Managing Director Ron Aderhold, respectively, co-authored an article in *ASM News* about the unique process used for strategic planning this year. Also in the "firsts" column was the use of Zoom breakout sessions for board and staff brainstorming as part of strategic planning. The technology replicates the in-person experience of dividing out into subgroups. I participated and have to say the technology was impressive.

Opening remarks at the ASM Annual Meeting.

September also included a virtual Leadership Days spanning two weeks. Breakout sessions were used for discussions on diversity, equity, and inclusion, and two networking happy hours helped foster interaction among attendees.

ASM's upcoming new event, IMAT — The Virtual Edition, October 26-28, will also offer online networking events in addition to premier technical talks and an exhibit hall experience. It is remarkable how many ways we can stay connected with our members and the engineering community through these software tools.

Another new tool growing in usage is ASM Connect and its discussion forums. Marin Manole of SP Foundry, posted this query: "What do you feel is the future of 3D metal printing, and what is the real cost of parts made using this process?" Here is a portion of the reply from Zachary Birky of Caterpillar: "Keep in mind that we are only a few years (5-20) into the development of AM. Yes, there are many quality problems facing current AM parts (internal porosity, surface finish, build speed, residual stresses). However, as the industry grows and thinks of new ways to improve quality, there will be increased adoption of AM usage."

And we'll be here to report those firsts to the ASM community.

Joanne Miller

joanne.miller@asminternational.org

RESEARCH TRACKS

Diran Apelian, FASM, director and founder of the Advanced Casting Research Center.

ADVANCED CASTING RESEARCH CENTER MOVES TO UCI

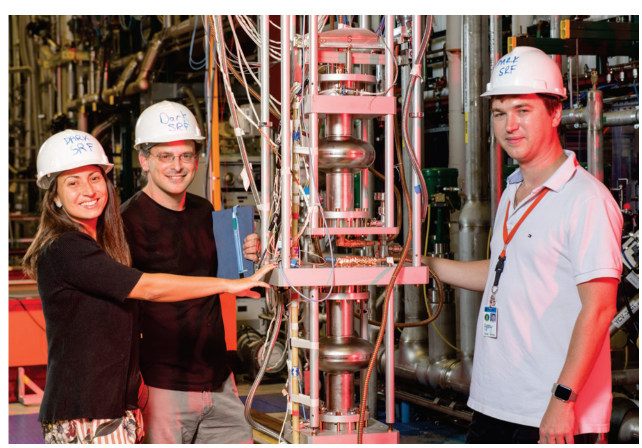
The Advanced Casting Research Center (ACRC) has relocated to the University of California, Irvine (UCI), effective July 1. Formerly, ACRC was based at Worcester Polytechnic Institute (WPI) in Massachusetts. Founding director Diran Apelian, FASM, was recently appointed Distinguished Professor at UCI's department of materials science and engineering. Earlier this year, he retired from his position as Alcoa-Howmet professor of mechanical engineering at WPI after 30 years. Apelian is widely recognized for his innovative work in metal processing and his leadership as a researcher and educator. Under Apelian's direction, the center will continue to bring fundamental understanding to existing processes, develop new methods, and address management-technology interface issues with industrial partners.

ACRC provides a collaborative environment in which members, faculty, and students discuss challenges in the metal casting and manufacturing industry, specifically in two main domains—alloy development and novel processes. The center was founded in 1985 with a small group of companies to advance the use of light metals. Over the years, it has become one of the larger industry-university alliances in North America carrying out fundamental research with clear industrial applications. With its new home in Southern California, ACRC will expand the consortium to meet the needs of manufacturers on the West Coast, including suppliers to the aerospace and defense industries. To support the activities of ACRC, UCI's state-of-the-art metal processing facility includes a modern foundry (ferrous and non-ferrous), vacuum arc melting, atomization unit, Buehler Center for metallography, Olympus microscopy suite, mechanical testing facilities, and nondestructive evaluation equipment. *acrc.manufacturing.uci.edu.*

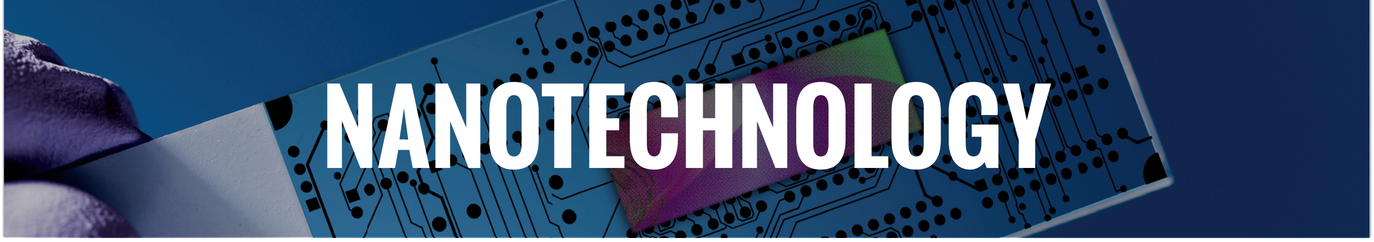
PROBING QUBITS WITH MATERIALS SCIENCE

The DOE's Fermilab, Batavia, Illinois, was recently chosen to lead one of five national centers to bring about transformational advances in quantum information science as part of the U.S. National Quantum Initiative. The initiative will fund the new Superconducting Quantum Materials and Systems (SQMS) Center, with the goal of building an advanced quantum computer based on superconducting technologies. The center will also develop new quantum sensors, which could lead to the discovery of the nature of dark matter and other elusive subatomic particles. Total planned DOE funding for the center is $115 million over five years. SQMS will also receive an additional $8 million in matching contributions from center partners. The new center is part of a $625 million federal program to facilitate and foster quantum innovation in the U.S. The leaps in quantum computing and sensing that SQMS aims for will be enabled by a unique multidisciplinary collaboration that includes 20 partners from the national laboratories, academic institutions, and industry.

At the heart of SQMS research will be solving one of the most pressing problems in quantum information science: the length of time that a qubit, the basic element of a quantum computer, can maintain information, also called quantum coherence. To advance coherence, SQMS collaborators will launch a materials science investigation to gain insights into the fundamental limiting mechanisms of cavities and qubits, working to understand the quantum properties of superconductors and other materials used at the nanoscale and in the microwave regime. Northwestern University, Ames Laboratory, Fermilab, Rigetti Computing, NIST, the Italian National Institute for Nuclear Physics, NASA Ames Research Center, and several universities are partnering to contribute world-class materials science and superconductivity expertise to target sources of decoherence. *sqms.fnal.gov.*



The Superconducting Quantum Materials and Systems Center plans to build a highly advanced quantum computer. Courtesy of Reidar Hahn/Fermilab.



NANOTECHNOLOGY

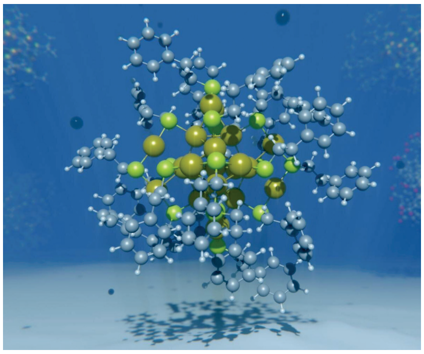


Illustration of the University of Pittsburgh's CANELa lab's nanocluster modeling. Courtesy of Mpourmpakis and Cowan.

MODELING NANOCLUSTERS

At the University of Pittsburgh's Swanson School of Engineering, the Computer-Aided Nano and Energy Lab (CANELa) is advancing the field of nanotechnology, modeling metal nanoclusters that are atomically precise in structure. With a better understanding of such small systems, researchers can more accurately apply theory and investigate how nanoclusters depend on their structure.

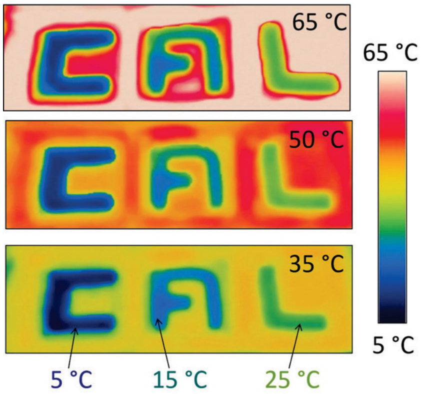
According to CANELa researchers, one of the key advances the lab has made to the field is modeling the specific number of gold atoms stabilized by a specific number of ligands. Ligand-protected metal nanoclusters are a unique class of nanomaterials that are sometimes referred to as "magic size" nanoclusters because of their high stability when they have specific compositions.

Predicting new alloys and previously undiscovered magic sizes is the next step that the field—and the lab—will need to tackle. The lab uses computational chemistry methods to model known nanoclusters, but creating a complete database of nanocluster structure, property, and synthesis parameters will be the next step to apply machine learning and create a prediction framework. *pitt.edu.*

THERMAL CAMOUFLAGE COATINGS

Researchers at University of California, Berkeley discovered a way to imbed visual decoys into surfaces of objects using delicately engineered thin films of tungsten-doped vanadium dioxide. Under infrared light, the resulting structures can be manipulated so onlookers perceive false images on the surface. Infrared light is invisible to the human eye, but can be detected by a range of devices, such as night-vision goggles and thermal-imaging cameras. The researchers' new coatings can effectively tune target objects into emitting the same infrared radiation as the surrounding environment, making them invisible to infrared detection devices.

To create the structures, the researchers focused on coating objects with tungsten-doped vanadium dioxide, a substance that at certain temperatures can phase shift from an insulator to a metal. With judicious engineering of the doping profile, the insulator-metal phase transition can even out, allowing the substance to emit a constant level of thermal radiation over wide ranges of temperature variations. This state of equilibrium prevents a camera from detecting the true infrared signals that an object normally emits around room temperature. Additionally, by manipulating the configuration and composition of tungsten-doped vanadium dioxide on coatings applied to special adhesive tape, researchers can create an infrared decoy.



The letters C-A-L appear cool even when the environment is hot. Using this technology, engineers develop decoys to fool infrared cameras into perceiving a designated temperature rather than the actual temperature of the object. Courtesy of Kechao Tan.

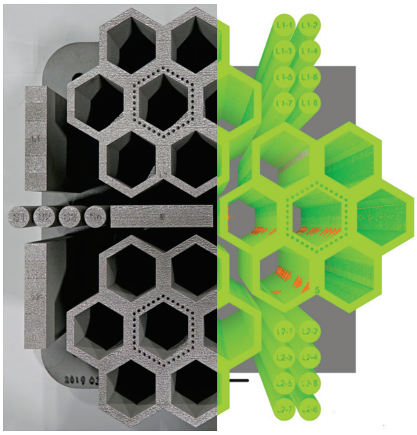
This kind of technology could prove useful for military and intelligence agencies as they seek to thwart increasingly sophisticated surveillance technologies that pose a threat to national security. It might also incubate future encryption technology, allowing information to be safely concealed from unauthorized access. *berkeley.edu.*

BRIEF

Scientists at the **University of Vermont,** Burlington, invented a new tool that can catch and straighten out molecule-sized tangles of polymers. Calling it a "nanocage," the scientists explain their tool is composed of molecular edges with special shape-directing hydrogen bonds. It can select out shorter strands of a polymer, leaving longer ones behind, demonstrating that the nanocage can be used to selectively find particular sizes of molecules in a web of material. *uvm.edu.*

Mona Sharafi assisted in constructing this "nanocage," which may help create new types of industrial materials. Courtesy of Joshua Brown/UVM.

MACHINE LEARNING | AI



Peregrine software detects an anomaly in a component being made on a powder bed printer. Courtesy of Luke Scime/ORNL.

SOFTWARE ASSESSES 3D PRINT QUALITY

Scientists at the DOE's Oak Ridge National Laboratory (ORNL), Tenn., recently developed artificial intelligence software called Peregrine for powder bed 3D printers. The program assesses parts quality in real time, without the need for characterization equipment. To devise a control method for surface-visible defects that would work on multiple printer models, the team created a novel convolutional neural network—a computer vision technique that mimics the human brain in quickly analyzing images captured from cameras installed on the printers.

The software uses a custom algorithm that processes pixel values of images, taking into account the composition of edges, lines, corners, and textures. If Peregrine detects an anomaly that may affect part quality, it automatically alerts operators so adjustments can be made. The software is well suited to powder bed printers, which are popular for producing metal parts. However, problems during printing such as uneven distribution of the powder or binding agent, spatters, insufficient heat, and porosities can result in defects at the surface of each layer.

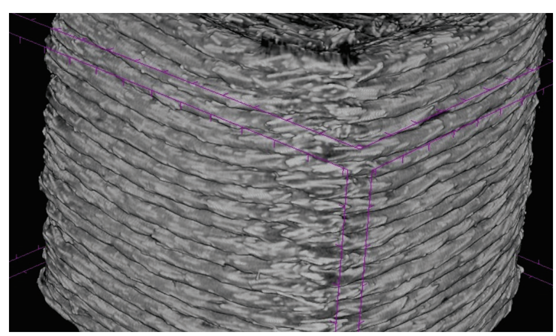
"One of the fundamental challenges for additive manufacturing (AM) is that you're caring about things that occur on length-scales of tens of microns and happening in microseconds, and caring about that for days or even weeks of build time," says principal investigator Luke Scime.

Peregrine is being tested on multiple printers at ORNL. The researchers stress that by making the software machine-agnostic, printer manufacturers can save development time while offering an improved product to industry. Peregrine produces a common image database that can be transferred to each new machine to train new neural networks quickly, and it runs on a single high-powered laptop or desktop. *ornl.gov.*

MACHINE LEARNING ENABLES REVERSE ENGINEERING

Key to the strength and versatility of glass and carbon fiber reinforced composites is the orientation of fibers in each layer. Recent innovations in 3D printing have made it possible to finetune this factor, due to the ability to include printer-head orientation instructions within the CAD file for each layer of the part being printed. However, a research team from NYU Tandon School of Engineering showed that these toolpaths are also easy to reproduce—and therefore steal—with machine learning (ML) tools applied to the microstructures of the part obtained by a CT scan.

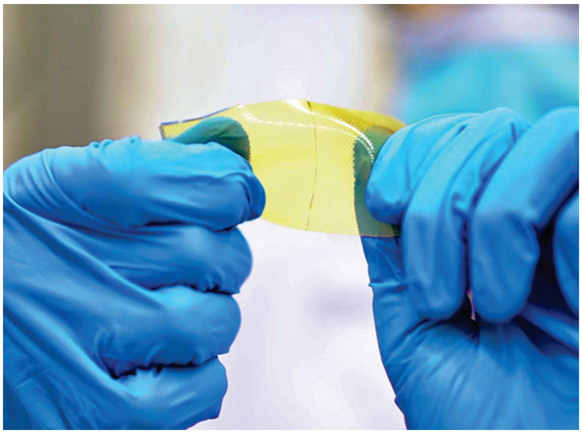
The team showed that the printing direction can be captured from the printed part's fiber orientation via micro-CT scan image. However, since the fiber direction is difficult to discern with the naked eye, researchers used ML algorithms trained over thousands of micro-CT scan images to predict the fiber orientation on any fiber-reinforced 3D-printed model. The study raises concerns for the security of intellectual property in 3D-printed composite parts, where significant effort is invested in development but modern ML methods can make it easy to quickly replicate them at low cost. *engineering.nyu.edu.*



Reconstructed CT scan model of a 3D-printed composite part shows overall dimensions and geometry.

BRIEF

Researchers at Japan's **National Institute for Materials Science** and **Toyota Motor Corp.** developed a technique that feeds information from aluminum alloy databases into a machine learning model. This trains the model to understand the relationships between an alloy's mechanical properties and its elements, as well as the type of heat treatment applied during manufacturing. The model can then predict what is required to manufacture a new alloy with specific mechanical properties. *www.nims.go.jp/eng.*



A new family of polymers can self-heal, have shape memory, and are recyclable. Courtesy of Matt Linguist/ Texas A&M Engineering.

VERSATILE SYNTHETIC MATERIALS

Researchers at Texas A&M University, College Station, and the U.S. Army Combat Capabilities Development Command Army Research Laboratory, Adelphi, Md., created a family of synthetic materials that range in texture from ultra-soft to extremely rigid by tweaking the chemistry of a single polymer. The researchers say their materials are 3D-printable, self-healing, recyclable, and naturally adhere to each other in air or under water.

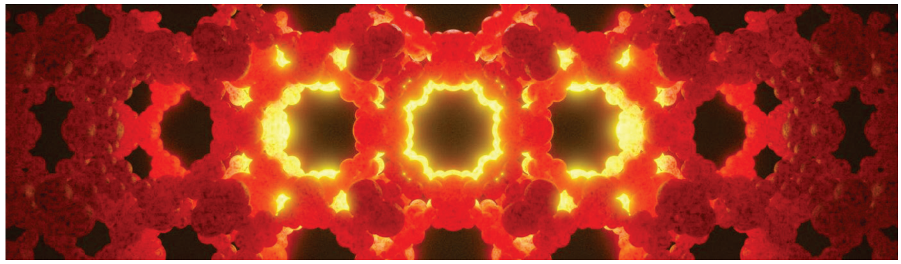
The researchers focused on the molecules involved in the crosslinking of elastomers. First, they chose a parent polymer, or prepolymer, and then chemically studded these prepolymer chains with two types of small crosslinking molecules—furan and maleimide. By increasing the number of these molecules in the prepolymer, they found that they could create stiffer materials. In this way, the hardest material they created was 1000 times stronger than the softest.

However, these crosslinks are also reversible. Furan and maleimide participate in a type of reversible chemical bonding. In this reaction, furan and maleimide pairs can "click" and "unclick" depending on temperature. When the temperature is high enough, these molecules come apart from the polymer chains and the materials soften. At room temperature, the materials harden because the molecules quickly click back together, once again forming crosslinks. Thus, if there is any tear in these materials at ambient temperatures, the researchers showed that furan and maleimide automatically re-click, healing the gap within a few seconds. The scientists say the new group of materials could have diverse military applications as well as aid in developing more realistic prosthetics and soft robotics. *tamu.edu.*

FUEL STORAGE WITH METAL ORGANIC FRAMEWORKS

An interdisciplinary team from six institutions is examining heat transfer in metal organic frameworks (MOFs) and the role it plays when MOFs are used for storing fuel, discovering that keeping cool temperatures is essential for potential applications. "One of the challenges with using MOFs for fuel tanks in cars is that you have to be able to fill up in a few minutes or less," explain the researchers. "Unfortunately, when you quickly fill these MOF-based tanks with hydrogen or natural gas, they get very hot. The whole premise of using them to store a lot of gaseous fuel only works at room temperature."

As such, the research looked at thermal transport in MOFs to explore how quickly they can shed excess heat. They conducted two simultaneous experiments using two different methods and MOFs synthesized in two different



Depiction of metal organic frameworks (MOFS). Courtesy of Christopher E. Wilmer/University of Pittsburgh.

BRIEF

With a $4 million grant from the DOE, researchers from **Missouri University of Science and Technology** and **Colorado School of Mines** are working to prove the economic viability of increased renewable energy use in steel production. The project would create a system that combines a hydrogen-reduction reactor for ironmaking (H2DR) with electric furnace melting for steelmaking. *energy.gov.*

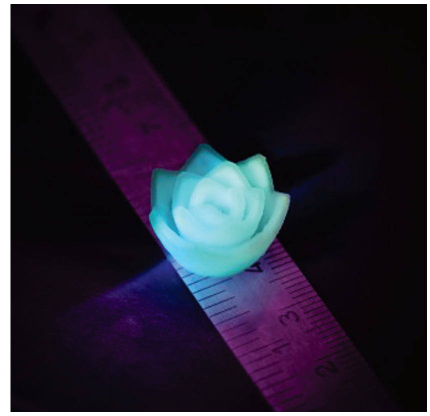
labs. Both groups observed the same trend—the MOFs become more insulated when filled with adsorbates. Their findings were also validated by atomistic simulations at University of Pittsburgh in collaboration with Carnegie Mellon University. *pitt.edu.*

3D-PRINTED AEROGELS

Researchers from Empa, Switzerland, are producing stable, well-shaped microstructures from silica aerogel by using a 3D printer. The printed structures can be as thin as a tenth of a millimeter. The new aerogel has even better mechanical properties and can even be drilled and milled. This opens up completely new possibilities for the post-processing of 3D-printed aerogel moldings.

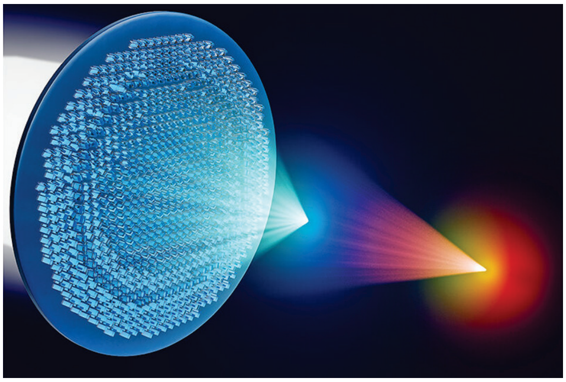
With the new patent-pending method, it is possible to precisely adjust the flow and solidification properties of the silica ink from which the aerogel is later produced, so that both self-supporting structures and wafer-thin membranes can be printed. As an example of overhanging structures, the researchers printed leaves and blossoms of a lotus flower. The test object floats on the water surface due to the hydrophobic properties and low density of the silica aerogel—just like its natural model. The new technology also makes it possible for the first time to print complex 3D multi-material microstructures.

With such structures it is now comparatively trivial to thermally insulate even the smallest electronic components from each other. The researchers also constructed a "thermos-molecular" gas, or Knudsen, pump. When it is placed under a light source, it becomes warm on the dark side and starts to pump gases or solvent vapors. But it can do more than just pump. If the air is contaminated with an environmental toxin, the air can circulate through the membrane several times and the pollutant is chemically broken down by a reaction catalyzed by the manganese oxide nanoparticles. Such sun-powered, autocatalytic solutions are particularly appealing in the field of air analysis and purification on a very small scale due to their simplicity and durability. *www.empa.ch.*



Researchers 3D-printed this lotus flower made of aerogel.

TESTING | CHARACTERIZATION



An illustration depicting how a metalens refracts light. Courtesy of Giuseppe Strangi & Federico Capasso.

RECONFIGURABLE METALENSES

Over the past decade, researchers at Harvard University, Cambridge, Mass., have begun to transform the field of optics by engineering flat optics metasurfaces, employing an array of millions of tiny, microscopically thin and transparent quartz pillars to diffract and mold the flow of light similar to glass lenses, but without the aberrations that naturally limit the glass. Now, the researchers and their collaborators have taken a step toward making these metalenses even more useful—by making them reconfigurable. Harnessing nanoscale forces to infiltrate liquid crystals between microscopic pillars allows the scientists to shape and diffract the light in completely new ways and essentially fine-tune the focusing power.

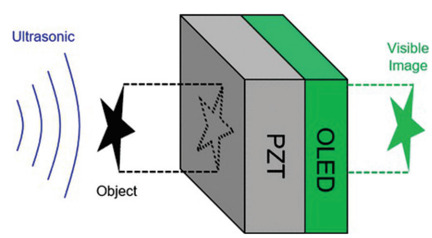
Liquid crystals are especially useful because they can be manipulated thermally, electrically, magnetically, or optically, which creates the potential for the flexible, or reconfigurable, lenses. Until recently, researchers say, once a glass lens was shaped into a rigid curve, it could only bend the light in one direction, unless combined with other lenses or physically moved. Metalenses changed that, since they allow engineering of the wavefront by controlling phase, amplitude, and polarization of the light. Now, by controlling the liquid crystal, the researchers have been able move this new class of metalenses toward new scientific and technological endeavors to generate reconfigurable structured light.

The technology was selected as among the "Top 10 Emerging Technologies" by the World Economic Forum in 2019, which remarked that these increasingly smaller, clearer lenses would soon begin to be seen in camera phones, sensors, optical fiber lines, and medical imaging devices such as endoscopes. "These tiny, thin, flat lenses could replace existing bulky glass lenses and allow further miniaturization in sensors and medical imaging devices." *harvard.edu.*

OLED ULTRASOUNDS

Researchers from North Carolina State University, Raleigh, developed a simpler and more cost effective approach for creating ultrasound images that eliminates the electrical signal processing step. To do this, they created a receiver that incorporates a piezoelectric crystal and an organic light-emitting diode (OLED). When an ultrasonic wave hits the crystal, it produces voltage, which causes the OLED to light up. Essentially, the image appears on the OLED screen, which is built into the receiver itself.

The proof-of-concept prototype is designed with a 10 x 10 pixel OLED array, but researchers say they can easily increase the pixels for better resolution. "Conventional ultrasound imaging probes can cost upward of $100,000 because they contain thousands of transducer array elements, which drives up manufacturing costs," they say. "We can make ultrasound receiver-display units for $100 or so." Potential near-term applications could



A simplified illustration of the newly developed ultrasound imaging device. Courtesy of North Carolina State University.

BRIEFS

The **National Science Foundation** awarded a $1 million grant to a team from the University of California, San Diego, University of Minnesota, Carnegie Mellon University, and Cornell University to create the X-ray Imaging of Microstructures Gateway (XIMG), designed to help researchers study the behavior of new and existing materials using x-ray diffraction. *ucsd.edu.*

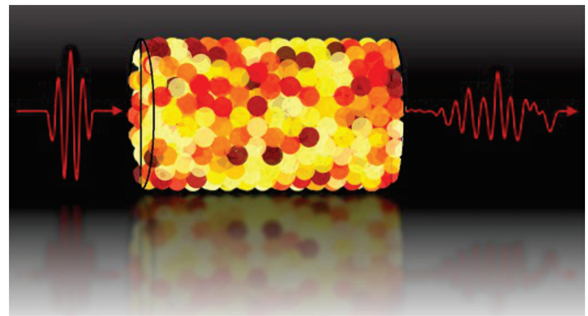
Case Western Reserve University researchers, Cleveland, are collaborating with the **U.S. Army** and three industry partners to advance manufacturing approaches for lightweight and high-performance polymeric materials. The Army's new five-year agreement awards $5.4 million to a team led by Case, with part of the funding to be used for lab equipment, including an electron microscope. *cwru.edu.*

include nondestructive testing, evaluation, and inspections for structural health monitoring. *ncsu.edu.*

MEASURING GRANULAR PROPERTIES

A team of researchers from Lawrence Livermore National Laboratory, Calif., used x-ray measurements and analyses to show that velocity scaling and dispersion in wave transmission is based on grainy particle arrangements and chains of force between them, while reduction of wave intensity is caused mainly from grainy particle arrangements alone. Stress wave propagation through granular material is important for detecting the magnitude of earthquakes, locating oil and gas reservoirs, designing acoustic insulation, and designing materials for compacting powders.

Structure-property relations of granular materials are governed by the arrangement of particles and the chains of forces between them. These relations enable design of wave damping materials and nondestructive testing technologies. "The novel experimental aspect of this work is the use of in-situ x-ray measurements to obtain packing structure, particle stress, and interparticle forces throughout a granular material during the simultaneous measurement of ultrasound transmission," the researchers say. "These measurements are the highest fidelity dataset to date investigating ultrasound, forces, and structure in granular materials." The research provides new insight into time and frequency-domain features of wave propagation in randomly packed grainy materials, shedding light on the fundamental mechanisms controlling wave velocities, dispersion, and attenuation in these systems. *llnl.gov.*



Two sets of data from x-ray scans of single crystal sapphire spheres are shown here with colorization representing the distribution of stresses for each grain under load.

PARTICULATE REINFORCED POLYMER MATRIX COMPOSITES: TRIBOLOGICAL BEHAVIOR AND 3D PRINTING BY FUSED FILAMENT FABRICATION

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A brief literature review and case study explore the effect of particulate reinforcements and processing parameters on the tribological behavior of polymer matrix composites made by 3D printing via fused filament fabrication.

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As the rapidly growing global population drives to improve their standard of living, the demand for energy, healthcare, housing, transportation, and industrial products is also increasing at unprecedented rates. To address future societal needs, new materials and sustainable development solutions such as the circular economy (CE) must be realized. CE envisions a new way to design, make, and use resources[1]. Additive manufacturing (AM) has emerged as one of the most important technologies in disrupting global supply chains and playing a critical role in sustainable development. This technology also potentially fits into the CE model, as it can incorporate recycled and reclaimed materials during manufacturing[2]. AM is defined by ASTM as "a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies."[3]

Tremendous growth has occurred in the AM landscape with the introduction of commercially available high-end 3D printing machines suitable for industrial applications. In addition, the availability of desktop 3D printers, as well as open-source printers and platforms, has facilitated large-scale growth of distributed digital manufacturing. The paradigm shift in thinking, where one can turn a design into product on demand, is leading to new business models—challenging traditional means of product development and distribution, as well as disrupting established global supply chains.

In a recent review, Holmberg and Erdemir outlined that tribology-based processes can lead to approximately 23% (119 EJ) of the world's total energy consumption[4]. They further calculated that 3% of this total corresponds to replacing worn out equipment, whereas 20% is consumed in overcoming frictional losses. Thus, the integration of AM and triboactive materials in a single platform can lead to a novel design paradigm. In this brief review, we will explore the effect of particulate reinforcements and processing parameters on the tribological behavior of polymer matrix composites fabricated by fused filament fabrication (FFF)-based 3D printing, also referred to as fused deposition modeling (FDM).

FDM was invented by S. Scott Crump in 1988 and patented in 1989[5]. FDM is the trademarked name of the process and is used interchangeably with FFF. ASTM F2792-12a defines this process as "a material extrusion process used to make thermoplastic parts through heated extrusion and deposition of materials layer by layer"[3].

FFF entails the design of customized filaments (Fig. 1), extrusion of filaments with a dimensional accuracy of 100 μm[6] by a nozzle, and design of a green body by depositing the filaments in a layer-by-layer sequence. This method is well-suited for manufacturing polymers with filled particles like ceramics and metals. Excellent reviews have summarized the recent progress in FFF-based materials research[7-11].

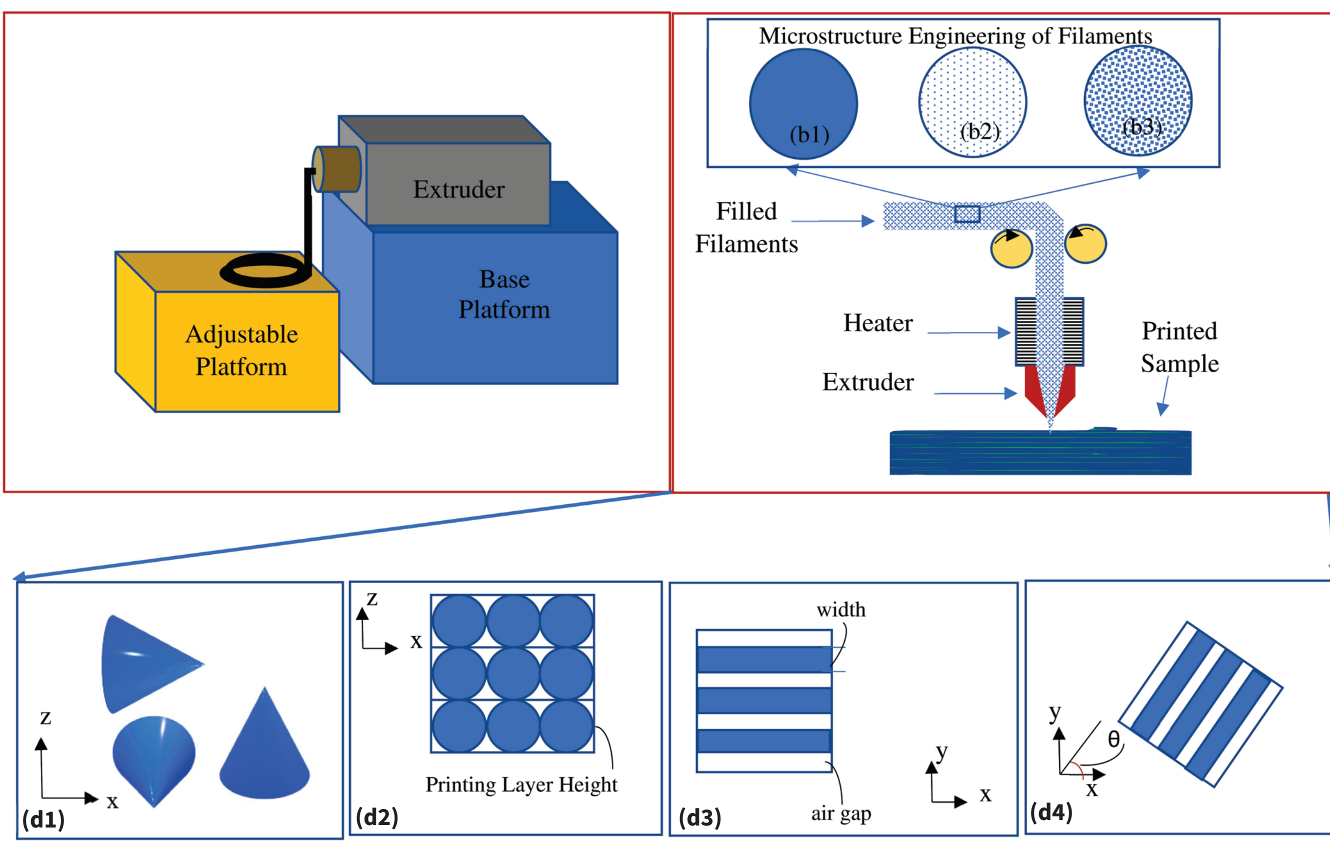

Fig. 1 — Top left, schematics of a filament extruder[12]; top, microstructure engineering of filaments, (b1) polymer, and reinforced with (b2) low and (b3) high volume of particulate reinforcements; top right, FDM setup being fed customized filaments; bottom, illustration of morphology of printed samples at different levels, (d1) orientation (y direction is into the plane of the paper), (d2) printing layer thickness, (d3) width, air gap, and (d4) raster angle (θ) with reference to x-axis[9].

For FFF, acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA) are the most studied polymers[6,9-10]. ABS is derived from petrochemicals, while PLA is renewable and biodegradable. In addition, other polymers like polyvinyl alcohol (PVA), poly-caprolactone (PCL), polyamide (Nylon), polyether ether ketone (PEEK), polyetherimide (PEI), high-impact polystyrene, and poly (oxymethylene) can be used for FFF[6-7].

Figure 1 shows the schematics of a customized filament-based FFF printer[12]. Hall et al. have customized a commercially available extruder (Filabot EX2 extruder; Filabot Lab) to design polylactic acid (PLA) filaments reinforced with up to 5 wt% ceramic particles like MAX phases (Cr_2AlC, Ti_3SiC_2, and Ti_3AlC_2) and MoAlB phases (Fig. 1a)[12]. They used a desktop 3D printer (H400 3D printer; Afinia 3D) to 3D print polymer-ceramic composites. This study shows that FFF has the potential to be commercially deployed as a low-cost system for entrepreneurs and small businesses. It is also possible to supplement a single printing head with a dual head to accelerate the printing process[7].

The top right of Fig. 1 shows the schematics of a pristine polymer base filament that is being fed into the extrusion head. These filaments can be filled with tailored particles. Additionally, fibers can be added separately to the filament during the extrusion process (in-nozzle impregnation method)[7]. The intent of the additions is to modify the properties of the polymeric matrix to improve its strength and/or to incorporate functional properties.

The printing process can be further engineered through different parameters (Fig. 1 bottom), including: orientation, usually horizontal (x-axis), vertical (z-axis), or lateral (y-axis); layer height (material deposited along the z-axis during a single cycle); raster width (width of the extruded layer); air gap (gap between extruded layers); raster angle (angle of deposition measured with respect to the x-axis); printing speed; infill density and pattern; nozzle temperature and diameter; and contour[9].

Based on a brief survey, the advantages of FFF include simple and tailorable process, flexible printing speed for different applications, entrepreneur and small business friendly, and environmentally benign if bioplastics are used. In addition, the microstructure can be engineered by filling in different additives such as metals (Cu, Fe, and others) and ceramics ($SrTiO_3$, MAX phases).

Daminabo et al. outlined some of the challenges of FFF, including layer trails due to deposition kinetics (stepped layers), sample collapse due to insufficient scaffold (also referred to as "overhang effect"), leak/loss due to localized melting of the filament (stringing), distortion/warpage due to internal stresses and/or thermal gradients, and nonuniform samples[6]. In their review, Solomon et al. summarized that the biggest limitations of this process are the inadequate availability of filament materials for FFF[9]. Popescu et al. summarized that the mechanical behavior of FFF components are anisotropic and dependent on the bonding between the printed layers[11]. This bonding can be further enhanced by tailoring layer thickness and raster width where thinner print layers enable better bonding. However, there is a trade-off of longer print times.

TRIBOLOGICAL BEHAVIOR

Mohamed et al. investigated the effect of layer thickness, fill gap, fill angle, build direction, raster width, and number of walls on the tribological behavior of PC-ABS (proprietary high-performance ABS developed by Stratasys Inc.) using pin-on-disk testing against EN31 steel discs[13]. They observed that wear rate decreased when the layer thickness was decreased. Comparatively, wear rate increased as raster angle and air gap were increased.

Srinivasan et al. investigated the effect of infill density, layer thickness, and infill pattern on the tribological behavior of ABS with the pin-on-disc method during dry sliding[14]. Their team concluded that the property of these solids can be enhanced by lowering layer thickness and increasing infill density; they also recommended using a grid pattern. Sood et al. outlined that scratching, fatigue, crack formation, and breakage of adhesive bonds were responsible for pit formation and wear in FFF-based ABS parts[15]. They also recommended that lower distortion is needed to prevent wear.

Prusinowski and Kaczy´nski investigated the tribological behavior of ABS and continuous fiber-reinforced ABS composites by using pin (ABS-based material)-on-disc (40 HM steel)[16]. They studied the effect of layer thickness and filler content as part of this study. They observed that fibers were effective in enhancing the wear resistance of ABS composites during dry sliding.

Hall et al. used FFF to print PLA-based samples reinforced with MoAlB, Ti_3SiC_2, Ti_3AlC_2, and Cr_2AlC by using an infill of 99% and a layer thickness of 0.2 mm[12]. They reported that the addition of these phases can enhance the triboactive behavior of these composites. For example, the friction coefficient (μ_{mean}) decreased by approximately 76% of μ_{mean} in PLA after the addition of 1 wt% additives, but there was marginal or no decrease in wear rate.

Abdelaal et al. reported that layer thickness and impact angle had the most influence on 3D-printed PLA samples during water-silica impact testing[17]. Srinivasan et al. compared the tribological performance of ABS with PLA-20% carbon fiber composite[18]. They reported PLA-20% carbon has a better response than ABS. In addition, they also reported that infill density and layer thickness had a significant effect on the results.

Bustillos et al. reported a 14% enhancement in wear performance of PLA after the addition of graphene[19]. Hanon et al. reported that the addition of bronze improved the wear performance of PLA but had limited effect on the friction coefficient when testing against polished steel using a cylinder-on-plate reciprocating tribometer[20]. Ertane et al. also reported that the wear rate of PLA can be improved by using biogenic carbon (biochar generated by pyrolysis of wheat stem at 800°C for 2 h)[21]. For example, PLA reinforced with 30 vol%

TABLE 1 – SPECIFICATIONS OF FILAMENT USED DURING THIS STUDY

Company	Type	Color	Diameter (mm)	Density of Filaments (g/cc)
MakerBot Industries LLC, Brooklyn, NY	PLA	True Red	1.75 mm	1.2
colorFabb, Belfeld, The Netherlands	Bronze Fill PLA	Bronze		3.9
	Copper Fill PLA	Copper		3.9
Protoplant, Vancouver, WA	Magnetic Iron PLA	Black		1.8

biogenic carbon showed a lower wear when testing against an alumina ball. In addition, the friction coefficient also became stable during sliding, although the authors reported that designing PLA samples with a high volume of reinforcement can lead to difficulty in producibility due to nozzle choking.

Lin et al. reported that the tribological properties of PEEK-carbon fiber (CF) composites are dependent on the orientation of the fibers[22]. External additions like nanosilica also affected the tribological behavior due to a rolling effect. Zhang et al. showed that a 3D-printed Nylon 618-based gear showed better performance than injection-molded Nylon 66 gears while testing under low-medium torque[23]. Soundararajan et al. were able to manufacture polyamide 6 (PA6) filaments with up to 30 wt% TiO_2 additions[24]. They also showed that PA6 + 30 wt% TiO_2 has the lowest wear rate. Based on these results, the authors proposed that these materials can be used in automobile applications. Singh et al. developed filaments of Nylon 6 with Al_2O_3[25]. The authors concluded that the presence of Al_2O_3 particles enhanced the tribological performance of these composites, and they performed better than ABS.

CASE STUDY: PLA-BASED COMPOSITES

A commercially available MakerBot Replicator 2X 3D printer was used to print test coupons with 0.1, 0.2, 0.3, and 0.4-mm layer heights (PLT). The PLA filaments were printed with a bed temperature of 40°C and an extruder temperature of 200°C. As listed in Table 1, in addition to a non-composite PLA (MakerBot), other composite filaments were investigated that had powder additions of bronze (colorFabb), copper (colorFabb), and iron (Protopasta). Short strips were used for optical microscopy of polished cross sections.

The tribological behavior of the samples was investigated with a block-on-disc tribometer (CSM Instruments SA, Switzerland) by using 3D-printed blocks (~4 x ~4 x ~3 mm) against alumina discs (Ad Value Technology, Tucson, Arizona). All the 3D-printed samples were machined into the desired dimensions. The configuration where the 3D-printed layers were perpendicular to the substrate was used for tribological performance evaluation. A surface profilometer (Surfcom 480A, Tokyo Seimitsu Co. Ltd., Japan) was used to measure R_a (arithmetic surface roughness). All the 3D-printed blocks were also polished to a Ra <1 µm, and alumina discs were polished to Ra <3 µm.

The experimental conditions used during these studies were 5 N, 31.4 cm/s linear speed, 10 mm track radius, and a sliding distance of 500 m, respectively. In this article, the μ_{mean} of the results is reported, which was calculated by taking the average of mean friction coefficients of three data sets of similar compositions. The mass of the 3D-printed blocks and alumina were measured before and after the tribology testing with a weighing scale (model XA82/220/2X, Radwag Balances and Scales, Poland). In all cases, the mass was transferred from the 3D-printed sample to alumina discs. Because of this, the specific wear rate (WR) reported is representative of the 3D-printed samples. The specific WR was calculated from:

$$WR = (m_i - m_f)/(\rho N d) \qquad \text{(Eq 1)}$$

where, m_i is the initial mass, m_f is the final mass, ρ is density of the composite, N is the applied load, and d is the total distance traversed by the sample during the tribology testing. All the blocks and discs were then coated with Au/Pd by using a Balzers SCD 030 sputter coater (BAL-TEC RMC, Tucson, Arizona) for microstructure evaluation[12]. The microstructure evaluation of the polished samples was also performed by using this microscope in secondary (SE) and backscatter (BSE) mode.

Figure 2 shows the SEM micrographs of PLA-bronze (Figs. 2a-b), PLA-Cu (Figs. 2c-d), and PLA-Fe (Figs. 2e-f) samples after printing with printing layer thickness (PLT) of 0.2 mm. In all cases, the particles were uniformly distributed in the microstructure, although defects like porosity were observed in the samples. For comparison, inset of Figs. 2a, 2c, and 2e show the microstructure of different filaments filled with bronze, Cu, and Fe particulates. The filaments also showed that particles are uniformly distributed in the filaments.

Figure 3 plots friction coefficient (µ) vs. distance of PLA (Fig. 3a), PLA-bronze (Fig. 3b), PLA-Cu (Fig. 3c), and PLA-Fe (Fig. 3d) against alumina substrates. In the PLA-alumina tribocouple, the profile of µ vs. distance showed fluctuations after the initial break-in period. Figure 4 shows the tribological performance of PLA-based composites. For non-composite PLA, μ_{mean} decreased from 0.64 to 0.55 as the PLT was increased from 0.1 to 0.4 mm (Fig. 4a). Comparatively, the wear rate (WR) increased marginally from ~6.8×10^{-4} to ~8.9×10^{-4} mm^3/Nm as the PLT was increased from 0.1 to 0.4 mm (Fig. 4b). Figure 5a shows the PLA surface where wear scars are visible, and Figs. 5b-c show the corresponding alumina surface where PLA was transferred due to abrasive wear.

Srinivasan et al. reported a lower wear rate in PLA-20% carbon with minimum layer thickness of 0.075 mm, grid pattern, and 80% infill density by using pin-on-disc tests[18]. The authors hypothesized that it is due to the better strength of the densely packed systems. In an ABS system, Salem et al. reported that the tensile strength of ABS decreased from approximately 34 to 27.5 MPa as the PLT is increased from 0.1 to 0.4 mm[27]. Comparatively, Srinivasan et al. reported the lowest WR of ABS samples printed at 0.1 mm PLT, compared to 0.2 mm PLT during pin-on-disc testing by self-mating[14].

In this case study, we showed that the tribological performance improved as the PLT was increased when sliding against alumina. It is hypothesized that PLA samples printed with high PLT helps in forming effective tribofilms, which decreases the μ_{mean} accompanied with marginal increase in WR. In other words, the tribological behavior of PLA is also governed by the formation of tribofilms, which is dependent on PLT and other parameters as discussed earlier. Additional studies are needed to quantify these effects. Currently, we are studying the effect of PLT on the mechanical performance of PLA-based compositions for a direct correlation with tribological performance.

We compared the tribological behavior with PLA filled with Cu, Fe, and bronze particulates. PLA-bronze showed the best performance, where the μ_{mean} varied between approximately 0.45-0.47 in all cases. The WR also decreased marginally from 3.3 x 10^{-4} to 2.7 x 10^{-4} mm^3/Nm as the PLT was increased from 0.1 mm to 0.4 mm (Fig. 4). The μ vs. distance profile was also stable in the PLA-bronze/alumina tribocouple compared to the PLA/alumina tribocouple (Figs. 3a and b).

Figures 5d and 5e show the PLA-bronze surface where signs of abrasive wear and triboxidation (Triboconstituent A, Table 2) was observed. Comparatively, PLA and bronze smeared on the alumina surface to form transfer films due to wear of the PLA-bronze surface. This also resulted in triboxidation of bronze constituents

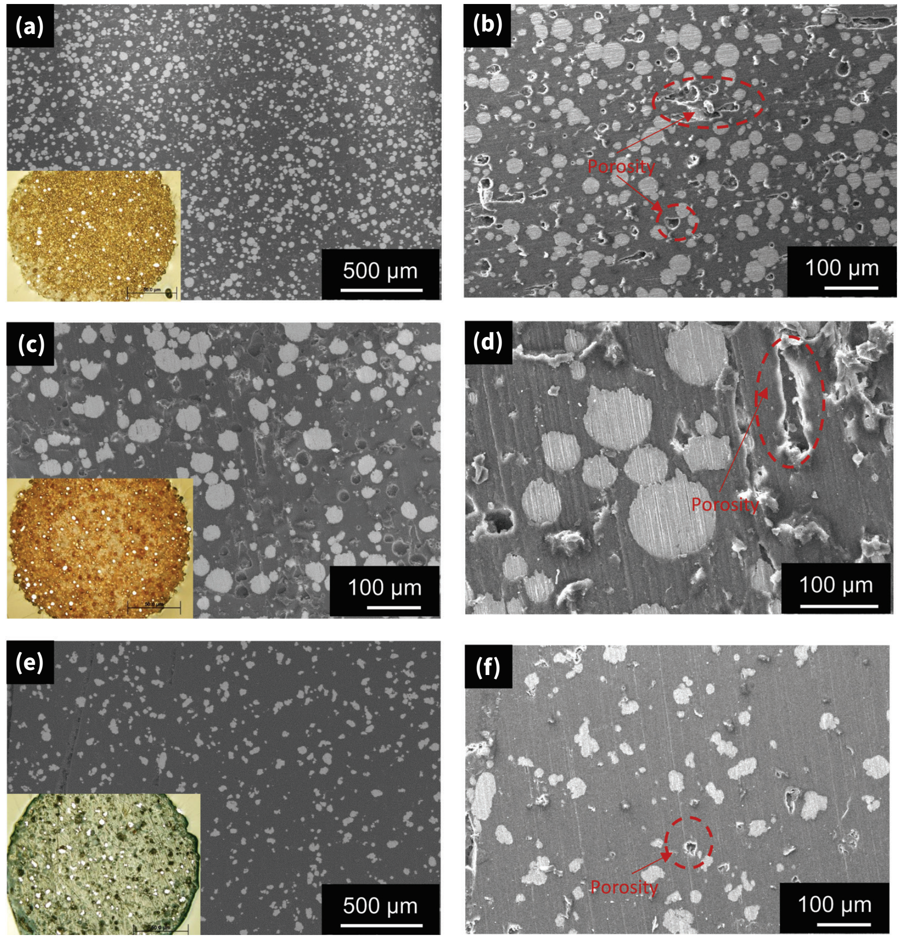

Fig. 2 — BSE SEM micrographs of polished cross section of: (a) PLA-bronze, (b) SE image of PLA-bronze (higher magnification), (c) PLA-Cu, (d) SE image of PLA-Cu (higher magnification), (e) PLA-Fe, and (f) SE image of PLA-Fe (higher magnification) after printing by PLT of 0.2 mm. Inset of (a), (c), and (e) show the optical micrographs of filaments of PLA-bronze, PLA-Cu, and PLA-Fe, respectively.

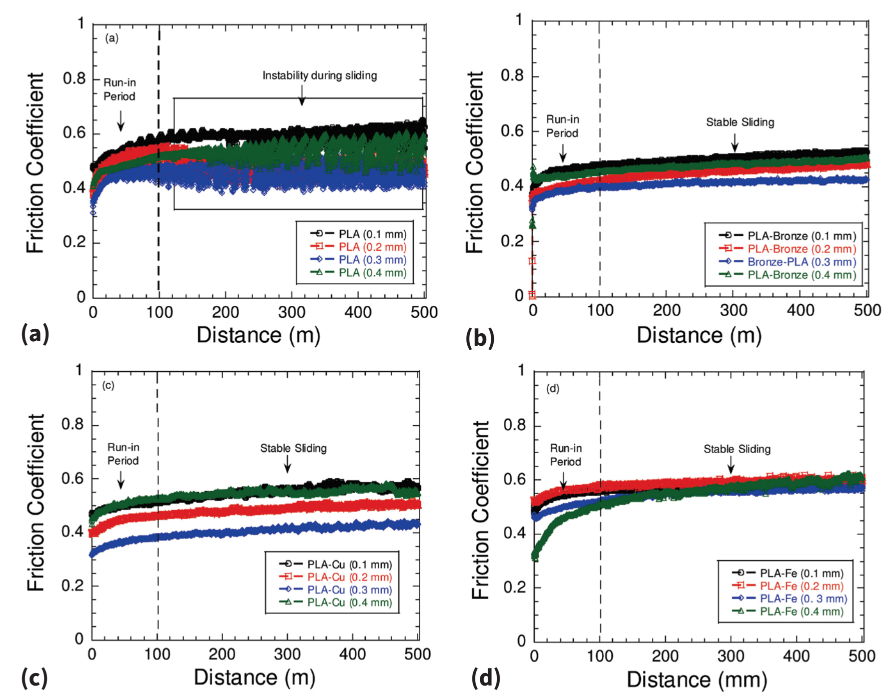

Fig. 3 — Plot of friction vs. distance of (a) PLA, (b) PLA-bronze, (c) PLA-Cu, and (d) PLA-Fe blocks during sliding against alumina.

(Figs. 5g-h; Triboconstituents B and D, Table 2). The evidence presented indicate that the formation of transfer films during testing also has an effect on the tribological behavior, where the formation of lubricious tribofilms lowered the μ_{mean}. Comparatively, PLA-Fe and PLA-Cu had μ_{mean} in the range of 0.51-0.56; the WR of PLA-Fe decreased from 5.9 x 10^{-4}

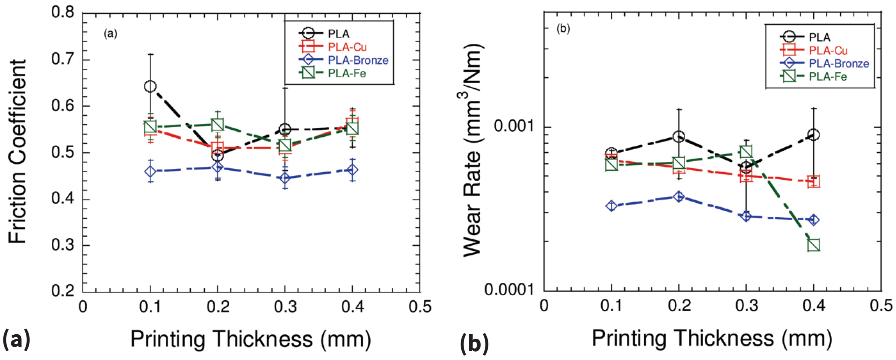

Fig. 4 — Plot of (a) μ_{mean} and (b) WR of PLA-based composites as a function of PLT.

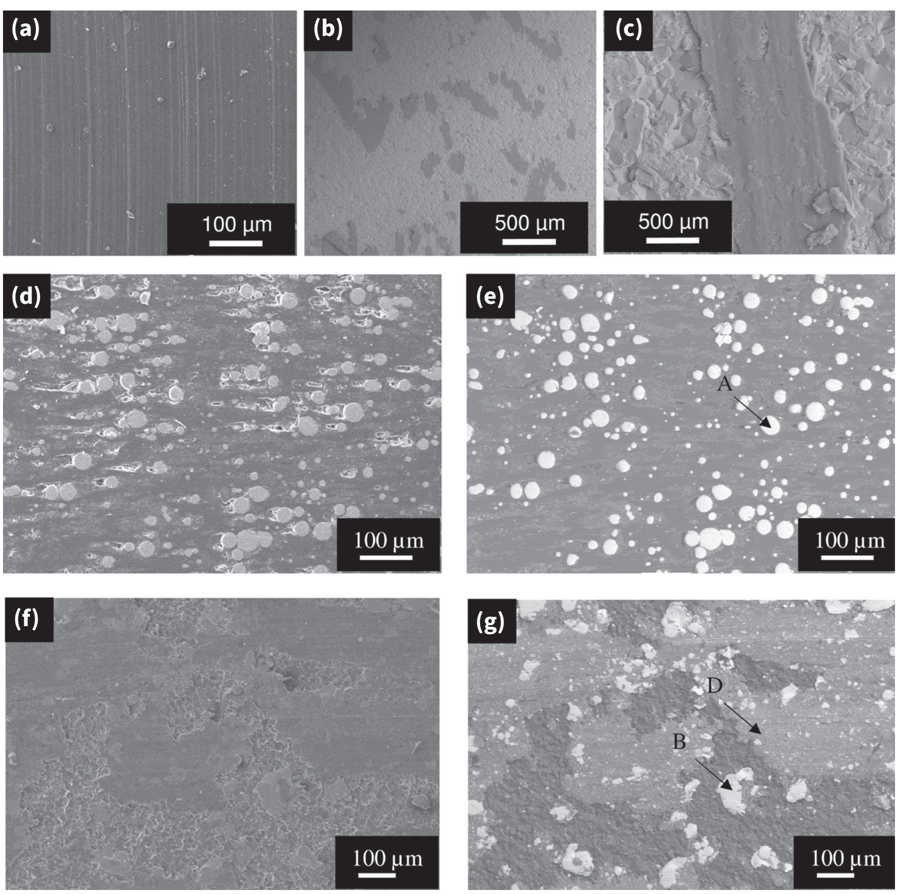

Fig. 5 — SE SEM images of (a) PLA surface and (b-c) corresponding Al_2O_3 surface, (d) PLA-bronze surface, (e) BSE of the same area and corresponding alumina surface in (f) SE, and (g) BSE of the same region during tribology testing against alumina (all samples printed using PLT of 0.2 mm).

to 1.9 x 10^{-4} mm^3/Nm, while in PLA-Cu, the WR decreased from 6.3 x 10^{-4} to 4.6 x 10^{-4} mm^3/Nm as the PLT was increased from 0.1 to 0.4 mm. The µ vs. distance profiles of these tribocouples were also stable compared to the PLA/alumina tribocouple (Figs. 3c, d). Ertane et al. also observed that the addition of biogenic carbon in PLA stabilized the µ vs. distance profile[21].

In the literature, detailed studies of tribofilms formed during tribological studies of 3D-printed samples are not well reported. Currently, we are performing detailed studies to understand the effect of PLT on mechanical performance and other physical properties. However, at this juncture, we can propose that the triboactive behavior of FFF-printed samples can be tailored by adding metal and ceramic particles. Based on the presented results, we can also propose that FFF-printed samples have potential in diverse triboactive applications as we transition into digital manufacturing.

CONCLUSIONS

FFF is a promising technology that can be tailored for use by entrepreneurs and small-scale businesses. More fundamental and applied research is needed in the design and development technologies for producing filaments. FFF is a highly adaptable technology for designing triboactive components by infiltrating the polymer with ceramic and metal particles. The current state of the art has successfully demonstrated its use at the laboratory scale. A further push for commercialization and pilot testing is recommended.

As a case study, it was demonstrated that various PLA-filled particles can enhance the tribological behavior. More specifically, PLA-bronze showed the best performance, where μ_{mean} varied between approximately 0.45-0.47 in all

TABLE 2 – EDS SUMMARY OF DIFFERENT TRIBOCONSTITUENTS

Composition	C	O	Si	Cu	Sn
A	22.7 ± 4.6	4.18 ± 0.31	0.94 ± 0.06	67.4 ± 5.17	5.14 ± 0.24
B	7.29 ± 0.89	2.19 ± 0.34	x	85.6 ± 0.77	4.89 ± 0.03
D*	36.9	13.4	0.57	42.6	2.55

*Single data point was used

cases, and the WR also decreased marginally from 3.2 x 10^{-4} to 2.7 x 10^{-4} mm^3/Nm as the PLT was increased from 0.1 to 0.4 mm. By evaluating the tribosurfaces, it is also hypothesized that, along with PLT and other printing variables, external factors like the formation of triboactive tribofilms has a significant role in controlling the tribological behavior of FFF-printed samples. **~AM&P**

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TECHNICAL SPOTLIGHT

METAL ADDITIVE MANUFACTURING: CONSIDERING THE RELATIONSHIP BETWEEN ALLOY AND APPLICATION

Case studies from a range of industries illustrate how advanced additive manufacturing capabilities optimize both material performance and value.

Additive manufacturing (AM) requires an interdisciplinary mindset. Design, materials, application objectives, and manufacturing technologies all play a role in the successful production and lifetime performance of 3D-printed parts. The design freedom made possible by AM can only be fully realized when the optimum material is chosen to execute the intended design—and the material will only perform at its best in a 3D printer that is up to the challenges the design itself presents.

Metal powder quality is generally no longer an issue, provided the powder comes from a reputable supplier. It is also recommended that multiple sources in the material supply chain be identified. Materials engineers have fine-tuned the methodologies with which existing metal alloys are commonly prepared for 3D printing via gas or plasma atomization of either wire or bar metal stock. In addition, the prices of many widely used powders have been coming down in recent years. Numerous time-tested, certified materials, once properly powdered, can now be printed. At the same time, superalloys created specifically for AM are becoming more available, delivering the exacting characteristics a particular industry requires for optimum part production.

The ability of AM to deliver previously impossible geometries with intricate internal structures is sparking the imaginations of engineers across many industries. Replacement parts can also be printed without the need to redesign for 3D printing. Whatever the goal, application requirements will always be the starting point when considering which material to use. Beginning with weldability (because AM is essentially a micro-welding process), these can include lighter weight, strength and rigidity, temperature range, thermal conductivity, and/or anodizability. AM system manufacturers often work directly with users to create appropriate manufacturing process parameters for each chosen material.

Titanium and aluminum alloys, along with Inconel and Hastelloy X superalloys, are some of the material blends currently in demand for 3D printing of mission-critical, regulatory approved, and extreme environment applications. How does one decide which material to use? Ask the design engineers who are driven by application requirements. As the industry examples below demonstrate, each of these materials brings with it a spectrum of qualities that best suit specific performance parameters.

CASE STUDIES

Inconel 718—Hanwha Power Systems is developing turbomachinery for a high-efficiency power generation system with solar energy as its heat source. Both temperature and pressure in such a system need to be very high, so the company designed a shrouded impeller in which the flow path of the working fluid is covered on both top and bottom (Fig. 1a).

While the nickel alloy Inconel 718 offered the high-temperature qualities

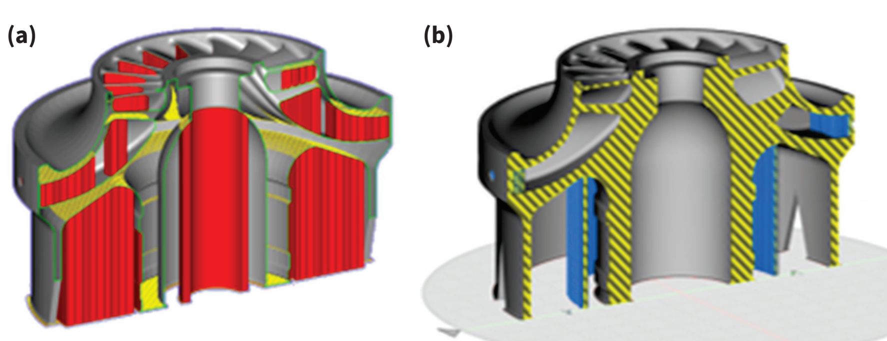

Fig. 1 — (a) Most of today's 3D printers would require a large amount of support structures (in red) to produce the Hanwha impeller design, while (b) a next-generation printer can manufacture the same design with minimal supports (in blue).

Hanwha was looking for, the part geometry was extremely complex and the material itself proved difficult to machine. In this case, 3D printing was a logical alternative choice, providing design freedom and avoiding welding and brazing of separate parts (Fig. 1b). Surface finish directly out of the advanced AM system was also exceptionally high, reducing post-processing steps.

Ti-6Al-4V—KW Micro Power is developing small, powerful, affordable hybrid-electric microturbines for drones and portable power generation. Their microturbine generator can produce more power than systems 10 times as large. At the heart of the company's turbine technology is a titanium disc with a 10-in. diameter and 4-in. height, whose interior contains a complex labyrinth that channels exhaust gases far more efficiently than conventional systems.

The Ti-6Al-4V alloy the company chose for its desirable weight and strength characteristics can be a challenge to work with. It is prone to cracking when 3D printed in many current systems. The material is ideal for building the microturbine's elaborate internal structures and zero-degree overhangs—although most AM technologies would require numerous scaffold-like supports to keep the workpiece from drooping and warping during the build process. In this case, a next-gen AM system enabled the part to be printed on the very first run—with a bare minimum of support structures (Fig. 2). Software, hardware, and process control overcame the technical challenges of printing this complex titanium part.

Aluminum F357—In another scenario, aluminum F357, a foundry-grade aluminum alloy with attractive thermal characteristics, can be used to 3D print parts traditionally manufactured. While there are other aluminum alloys such as AlSi10Mg that are more commonly used in metal additive manufacturing, the high silicon content of this alloy means it cannot be anodized. In contrast, 3D parts printed from aluminum F357 can be anodized, thus inhibiting corrosion and providing greater durability in the field. This is a highly desirable attribute for heat exchangers in mission-critical applications—for which F357 has already been certified.

Fig. 2 — The as-printed KW Micro Power diffuser housing, top view (left) and bottom (right).

Fig. 3 — A variety of 3D-printed heat exchanger components (both whole and in cross section) demonstrate the design freedom provided by advanced AM technology. Note the ultrathin features in the core (cross section image). Such complexity is nearly impossible to attain with existing AM technologies.

That's why PWR, a global supplier of advanced cooling solutions to Formula 1, NASCAR, and other racing series—along with custom automotive, military, and aerospace heat-exchanger applications—chose this material (Fig. 3). The company worked with an advanced AM system provider to develop the process for 3D printing F357. Of particular importance are thin walls that are leak-tight, fully dense with no porosity, and have a good surface finish, all of which work together to enable thermal conductivity. Because this advanced AM technology allows the creation of extremely free-form and lightweight structures, PWR now has both the material and technology resources to further improve performance and packaging in a wide variety of heat-transfer applications.

Fig. 4 — Unicore of a 20-kW microturbine engine, being developed by Sierra Turbines, 3D printed on an advanced metal AM system. The nickel-base alloy is exceptionally resistant to stress corrosion cracking and oxidation and is most often used to manufacture parts for combustion-zone gas turbine engines due to its high temperature strength.

Hastelloy X—The final example involves Hastelloy X, a nickel-base alloy exceptionally resistant to stress corrosion cracking and oxidation. It is most often used to manufacture combustion zone components for gas turbine engines in both aerospace and power generation applications. Parts 3D printed with Hastelloy X are exceptionally strong, with cyclic fatigue strength, corrosion resistance, and creep resistance that deliver durability over time and decrease equipment downtime.

Sierra Turbines recently partnered with an advanced AM system provider to print a prototype for its 20-kW microturbine engine with an innovative unicore made with Hastelloy X (Fig. 4). Realizing that time between overhaul (TBO) for most small turbine engines averages 40 to 50 hours, the company has a goal of raising that to 1000+ hours (on par with commercial aircraft), due in large part to the durability of the superalloy. Other goals include reducing engine weight to a kilogram or less, something enabled by the design freedom and extreme part consolidation (61 parts down to one) provided by the support-free printing process of modern AM technology.

CURRENT VERSUS ADVANCED AM SYSTEMS

Historically, metal additive manufacturing systems have not been able to efficiently deliver desirable part characteristics without resorting to multiple print runs, a litany of post-processing steps, and/or extensive finished-part testing (both destructive and nondestructive). But recent advancements in process control, hardware innovation, and quality assurance are now producing first-run results in record time. These advanced AM systems are empowering engineering teams to make decisions about materials based on precise performance goals and achieve 3D-printed parts that meet or exceed the strictest specifications in their industries. ~AM&P

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MATERIALS SCIENCE AND CORONAVIRUS SERIES

USING DIGITALLY DISTRIBUTED MANUFACTURING TO ADDRESS CRITICAL NEEDS

America Makes has mobilized the additive manufacturing community to work together to address the nation's medical equipment shortages during the COVID-19 pandemic.

John Wilczynski, Alexander Steeb, Brandon Ribic, Andrew Resnick, Mark Cotteleer, and Corinne Charlton**
America Makes, Youngstown, Ohio

Imagine a world in which crisis response is automatic. Where a system exists to "surge" critical supplies into a crisis zone—local, regional, national, or global—regardless of what those supplies are, or who has historically produced them. Such is the work in which America Makes—The National Additive Manufacturing Innovation Institute—is currently engaged.

America Makes is leading the creation of the "Advanced Manufacturing Crisis Production Response" (AMCPR), a digitally distributed manufacturing platform and network, to address critical needs using additive and other advanced manufacturing (AM) technologies. By revolutionizing the domestic supply chain, and reconsidering the nation's stockpiling strategy, it aspires to accelerate the manufacture of products and to leave behind an enduring infrastructure to serve in the future. In building this capacity, America Makes is also raising awareness of the ways in which AM can add value at a national scale.

ADDRESSING PPE SHORTAGES

Traditionally, many U.S. manufacturing supply chains have been designed with low cost in mind, resulting in productive capacity that could be geographically removed from end users. When the new coronavirus struck, U.S. attempts to obtain and stockpile personal protective equipment (PPE), medical devices, and diagnostic testing equipment were too often hindered by local and global disruptions to supply chains. This inspired engineers, researchers, and designers to use resources already at their disposal and create products to address discrete needs—revealing tremendous latent capacity in the U.S. economy.

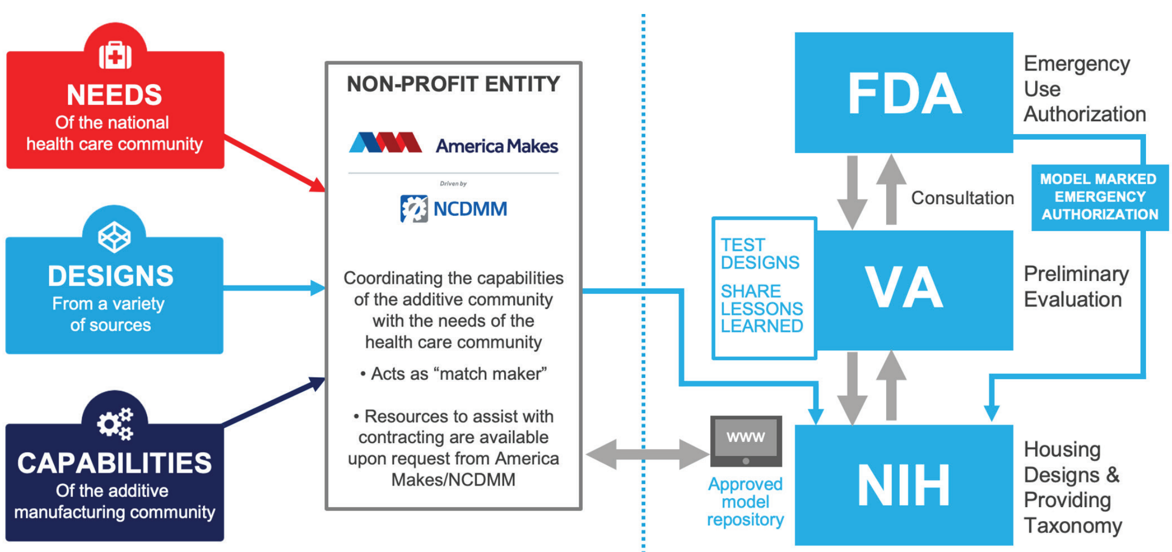

Fig. 1 — America Makes, driven by The National Center for Defense Manufacturing & Machining (NCDMM), is well-positioned as a public-private partnership to collect end-user needs, coordinate supply, catalyze designers from the private sector, and communicate policy and regulatory guidance from government bodies.

**Member of ASM International*

This reaction also exposed substantive challenges related to design validation (i.e., will it work?), IP and legal considerations (i.e., who owns the rights to it?), and the real demand for product (i.e., how do we get product to those in need?) that created friction in product delivery and implementation.

COORDINATION OF EFFORTS

America Makes quickly recognized the importance of coordinating these efforts, collaborating with the Department of Veterans Affairs (VA), Food and Drug Administration (FDA), and National Institutes of Health (NIH) (see Fig. 1) to mobilize the AM community to address medical equipment shortages. With their privileged position as a public-private partnership institute, they were able to effectively engage with both Federal agencies and industry partners.

America Makes collected information from engineers with novel designs, manufacturers capable of producing those designs, and demand requirements from those requesting the supply of PPE. Designs were printed and tested by the VA, and once reviewed, would be submitted onto the NIH model repository, where manufacturers could download the designs with appropriate use designations to produce. Within ten days, the effort had registered more than 400 manufacturers, with capacity to deliver 100,000 PPE items weekly. By June 2020, America Makes had facilitated connections resulting in delivery of more than 287,000 VA-reviewed medical components to those in need.

ENDURING INFRASTRUCTURE

America Makes' long-term goal is to use AM technologies to build an adaptable resource and reimagine the national stockpile to address future needs. During the 2020 pandemic, AM supplemented conventional manufacturing to create hybrid supply chains within the U.S., enabling higher efficiencies and identifying a unique value proposition for AM technologies. With new members from diverse fields such as healthcare and law enforcement, America Makes created a singular narrative to communicate the value of AM, and how individual engineers could play an important role in addressing the PPE shortage.

As the AMCPR effort continues to evolve, it will make use of the constellation of America Makes Satellite Centers (AMSCs) at the University of Texas-El Paso, Wichita State, and Texas A&M, along with other members of the AMCPR stakeholder community, to increase the manufacturing community's ability to address the point-of-need demand. AMSCs' extensive AM capabilities include a wide variety of assets, leading AM experts, industry and government partners, and relationships at top-tier research institutions, facilitating rapid testing and iteration. At the heart of the AMCPR effort will be a digitally distributed manufacturing network that seeks to reduce regulatory and economic barriers to production, especially for small and medium sized enterprises.

STRATEGIC RESERVES

The COVID-19 pandemic has demonstrated that maintaining a stockpile of critical equipment is not trivial. It cannot be known what the next event will look like, when it will occur, or what the associated needs will be. Furthermore, degradation of materials over time can lead to dangerous failures, and logistical challenges of equipment delivery can cause fatal delays. A transformational strategy will include a repository of designs and member networks, instead of physical products. The digital stockpile of vetted parts will better prepare and mitigate the impact of future crises on the nation. It will require reconsideration of what critical supplies are, and include warehousing of raw materials and feedstocks, which have their own shelf life and degrade over time.

ABOUT AMERICA MAKES

America Makes is the nation's leading public-private partnership for AM technology and education. Members from industry, academia, government, and workforce and economic development organizations, work together to accelerate the adoption of AM and the nation's global manufacturing competitiveness.

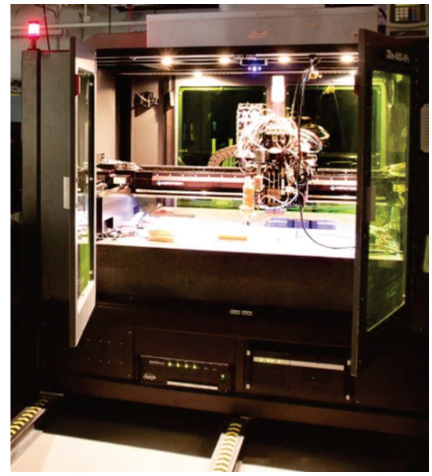

Fig. 2 — America Makes Satellite Center.

IMPACT ON AM COMMUNITY

The AM community's dedication in reacting to the pandemic demonstrates the adaptability and innovation within the industry. The rapid response, flexibility of design and materials, along with the distribution of capacity, uniquely positions AM as the solution to meet urgent regional needs. The resources and networks being built will serve as a foundation to validate industry-recognized credentials to develop a robust AM workforce, along with increased awareness and understanding of a technology which is still novel to much of the public.

The launch of the AMCPR is America Makes' effort to create a central resource to coordinate the domestic additive manufacturing ecosystem, respond to critical manufacturing needs, and enable delivery of safe, effective products. This effort represents a critical step forward for the United States in its ability to maintain and enhance the health and economic security of the country. **~AM&P**

Lead image: 2019-nCoV spike protein, courtesy of Jason McLellan/University of Texas at Austin.

For more information: Alexander Steeb, director of operations, America Makes, 236 W. Boardman St., Youngstown, OH 44503, 330.622.4299, alexander.steeb@ncdmm.org, americamakes.us.

LOCATING AND EXTRACTING RARE EARTH ELEMENTS FROM DOMESTIC COAL-BASED RESOURCES

Even with the recent downturn in coal production, the amount of coal being mined and utilized in the U.S. contains more than four times the current domestic consumption of rare earth elements.

Elliot Roth, KeyLogic Systems LLC, Morgantown, West Virginia

Mary Anne Alvin, National Energy Technology Laboratory, Pittsburgh

In the United States, coal is a vast natural resource that powered the Industrial Revolution and has dominated the electric power industry for decades. In 2018, the U.S. Energy Information Administration (EIA) estimated there are more than 253 billion short tons of domestic coal reserves—enough to energize the country for hundreds of years. The potential for coal to impact and revolutionize U.S. industries goes beyond its heating value. For example, the use of coal combustion by-products has seen tremendous growth in the production of construction materials such as concrete and wallboard.

Continuing to unlock coal's unique characteristics and future industrial capability has been an objective of the U.S. Department of Energy (DOE)/National Energy Technology Laboratory (NETL) for many years. The initiation of DOE/NETL's Feasibility of Recovering Rare Earth Elements program in 2014 further exemplifies the objective of unleashing coal's full potential with a focused effort to produce salable rare earth elements (REEs) from domestic coal and coal-based resources.

The importance of REEs cannot be overstated. With hundreds of end uses and applications in clean energy production, oil refining, electronics, batteries for electric vehicles, phosphors for lighting, and defense technologies, rare earths are critical to the stability and growth of modern society. However, the U.S. is heavily reliant on imports to supply REEs and compounds as well as intermediate and end products containing rare earths such as permanent magnets, motors, and turbines. This reliance on imports for REEs causes supply and price risk concerns. One possible solution is turning to abundant U.S. coal resources for a domestic, economical, reliable, and environmentally benign source of REEs. With an average concentration of 62 parts per million (ppm) of REEs in U.S. coal, there were more than 45,000 tons of REEs contained in coal mined in the U.S. in 2018—more than quadruple U.S. REE consumption[1]. Although this is a remarkable quantity of REEs, the challenge is developing economical separation technologies for producing REEs from coal and coal-based resources.

FIELD SAMPLING

To extract REEs from any source, materials characterization information must be initially obtained, which includes determining the concentration or grade of REEs in the source material, as well as the chemical phase or mineral in which the REEs are contained. With expansive coal reserves and millions to billions of tons of coal refuse, coal ash, and acid mine drainage (AMD) water and sludge scattered across the country[2-4], determining the best materials and samples, locations, and coal seams, as well as materials in terms of the contained REE concentration, is an extensive effort.

As part of NETL's REE program portfolio, projects are required to provide elemental characterization information for materials identified during prospecting efforts, as well as during processing where REEs are extracted through physical beneficiation, separated though chemical processing, and recovered as either mixed or individually separated rare earth oxides (REOs). This information is uploaded to NETL's Energy Data eXchange (EDX) website[4] for public use. In addition to these data, published REE datasets such as the U.S. Geological Survey (USGS) Coal Quality (COALQUAL) database[5,6] and journal publications are viewed as valuable

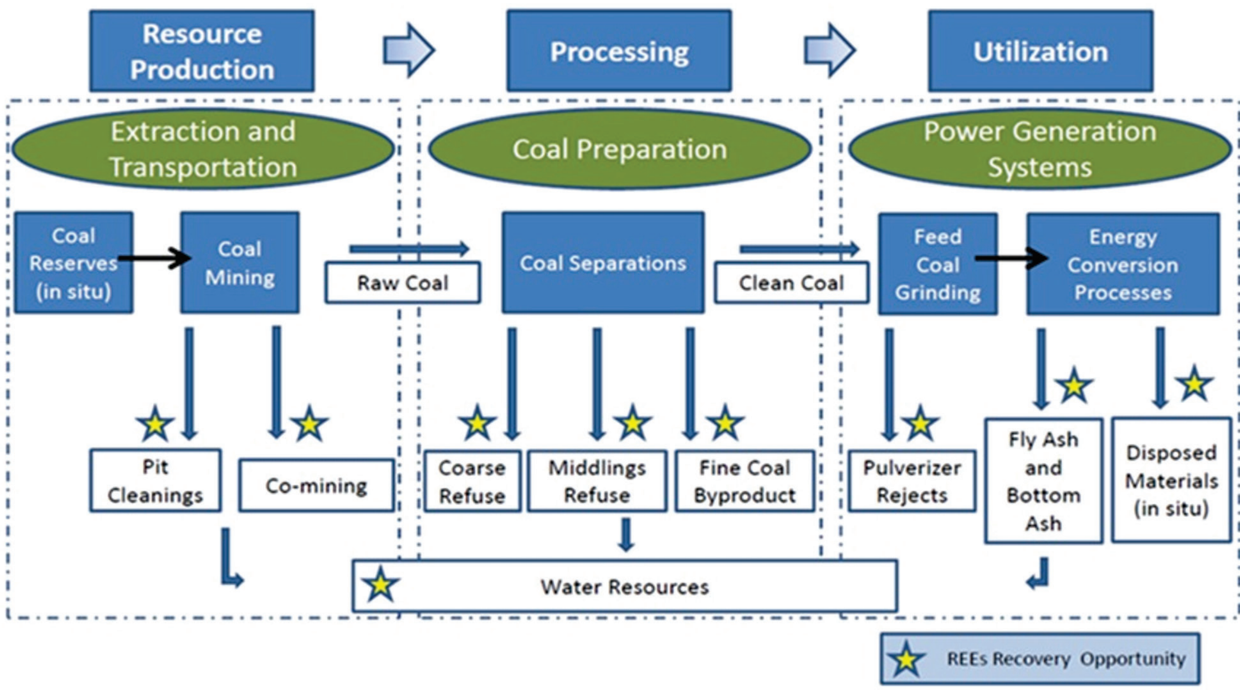

Fig. 1 — Coal-based materials for REE recovery[4].

sources of information for determining the feasibility of extracting REEs from coal-based resources. Materials generated along the coal value chain, shown in Fig. 1, create potential REE materials for REE extraction[2].

ENSURING DATA QUALITY

Determining the concentration of REEs in heterogenous matrices such as coal-based materials is not a trivial task. Therefore, it is important to have a data quality assurance protocol, particularly when comparing generated data from different analytical instruments and/or procedures. Fortunately, for the REEs, the smoothness of normalized REE distribution curves provides a simple yet reliable way of evaluating the quality of REE data[6-8].

Normalizing can be conducted using different standard REE concentrations, such as REE concentrations in chondrite meteorites, the Upper Continental Crust (UCC), the North American Shale Composite (NASC), or Post-Archean Australian Shale (PAAS) composite values. For coal and coal by-products, the standard used for normalization should be one that has been affected by similar geological fractionation processes[7]. In this article, the values are normalized to the UCC reported by Taylor and McLennan[9]. Figure 2 shows the UCC normalized curve for average U.S. coal reported by Finkelman[10]. The smooth line is an indication of good data quality, while the normalized value around 0.5 indicates that the concentration of REE in coal is approximately half the concentration found in the UCC for each element.

Large deviations from a smooth normalized curve as well as sawtooth patterns appear in the literature and are mostly associated with analytical error[6,7]. Some of the sample data posted on the NETL EDX website shows rough normalized patterns and should be used with caution. For example, Fig. 3 shows large anomalies for terbium, thulium, and lutetium, which indicate that the analytical results for these elements are suspect.

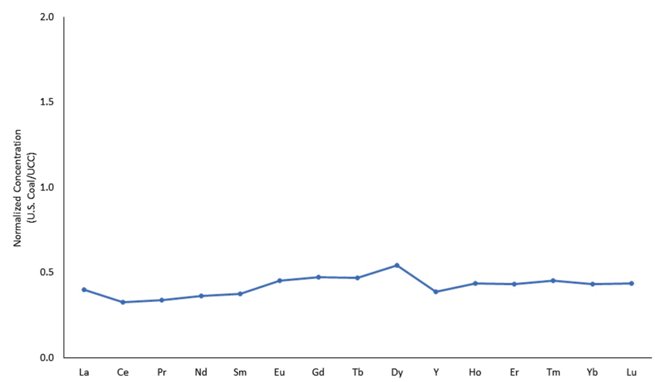

Fig. 2 — UCC-normalized average REE concentrations in U.S. coals.

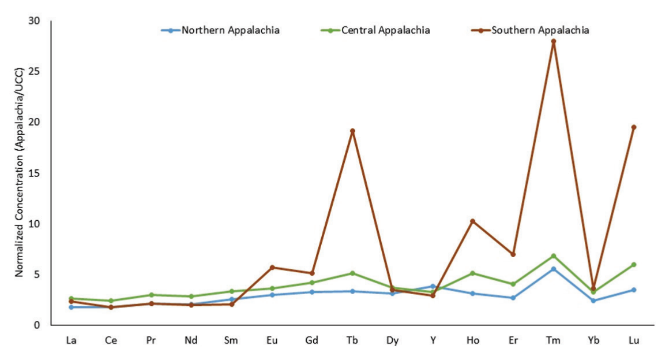

Fig. 3 — Average REE UCC-normalized data for coal and coal by-products from the Appalachia basins (dry ash basis).

REE CONCENTRATIONS

When reporting REE concentrations, it is important to specify which elements are included as part of the reported total REE (TREE) content. In this article, REE refers to the lanthanides and yttrium. REE concentrations that contain scandium are referred to as *REE+Sc*. Using this nomenclature, the average REE concentration in U.S. coal is between 62 and 65.5 ppm on a dry whole sample or dry mass basis[6,10]. This translates to more than 46,000 short tons of REEs being mined in U.S. coals in 2018, using the EIA 2018 U.S. coal production of 756 million short tons (MMst)[11]. This is more than four times the estimated apparent consumption of approximately 11,000 tons of REEs in 2015, and shows the potential opportunity for coal to meet U.S. REE demand[1]. Moreover, production and use of coal produces other large-volume materials, such as power generation ash, coal refuse, and AMD sludge, which can also be considered as potential REE sources.

Using NETL's EDX data, the average REE concentration on a dry ash basis for each U.S. coal basin is shown in Table 1. This table, which characterizes more than 3000 datasets, shows that AMD sludge exhibits the highest average REE concentration compared to coal and coal by-product samples analyzed to date. The higher REE concentration in AMD sludge has renewed interest in these materials as a potential REE source. The Central Appalachia basin features the highest average REE concentration. This supports publications that have shown enriched REE concentrations in the bituminous fire clay coalbed in eastern Kentucky.[12,13]

The relatively high REE concentrations found in AMD sludge potentially open new opportunities for extracting coal-based REEs that could not have been fully appreciated by examining large datasets in the published literature, such as the COALQUAL database and REE concentrations in coal mine drainage water samples[6,14]. Additionally, AMD sludge contains a higher heavy REE (HREE) concentration (Fig. 4) in comparison to other coal-based materials.

TABLE 1 – REE DRY ASH BASIS CONCENTRATIONS FOR COAL AND COAL BY-PRODUCTS BY DOMESTIC U.S. BASIN

Basin	N	REE (ppm)
Northern Appalachia AMD Sludge	573	728
Central Appalachia AMD Sludge	70	521
Northern Appalachia	400	354
Central Appalachia	279	509
Southern Appalachia	35	343
Illinois	769	332
Rocky Mountain	120	113
West/Northwest	2	334
Gulf Lignite	30	242
Powder River Basin	93	364
Lignite	416	319
Other*	264	381
Total	**3051**	

Note: N is number of datasets; REE [ppm] is average concentration.

*Samples include materials from unidentified plants, blended ash samples, roadcuts, and other coal-based samples. No attempt was made to infer a basin if the EDX website data did not identify a basin.

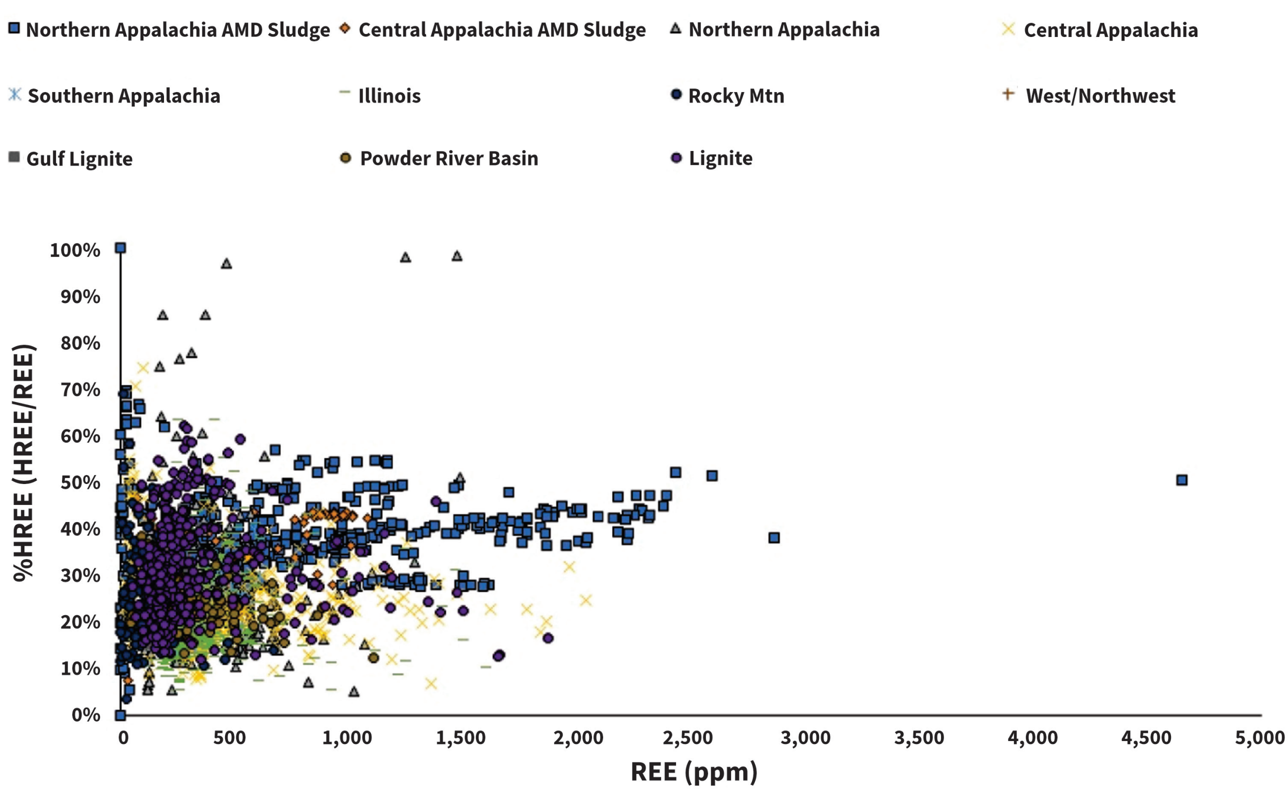

Fig. 4 — Percent HREE (Tb through Lu, Y) compared to total REE concentration.

When examining the distribution of REEs in a sample, it is important to recognize that supply and demand—and therefore the price of individual REEs—varies widely. While some HREEs have a high price, there may be a limited market, which should be considered when examining various materials as a potential source of REEs. Some REEs may also be considered critical depending on the application, such as REEs for clean energy. DOE has identified five critical REEs, including yttrium, neodymium, europium, terbium, and dysprosium. Several Northern Appalachia AMD sludge samples were identified to have concentrations above 2000 ppm and greater than 50% critical REE. The total critical element concentration is valuable when considering which materials should be examined further for economical extraction of REEs.

CONCLUSIONS

Even with the recent downturn in U.S. coal production, the amount of coal being domestically mined and utilized contains more than four times the current U.S. consumption of REEs. With the U.S. being import-reliant on REEs for use in advanced technologies for energy and defense, a tremendous opportunity exists for coal and coal-producing areas to extract these valuable and strategic elements. NETL is currently leading the effort to locate the best coal or coal-based resources for REE and critical materials extraction. This effort encompasses the entire coal value chain. With chemical characterization analyses of more than 3000 datasets, valuable findings such as the high REE concentration in AMD have been realized. **~AM&P**

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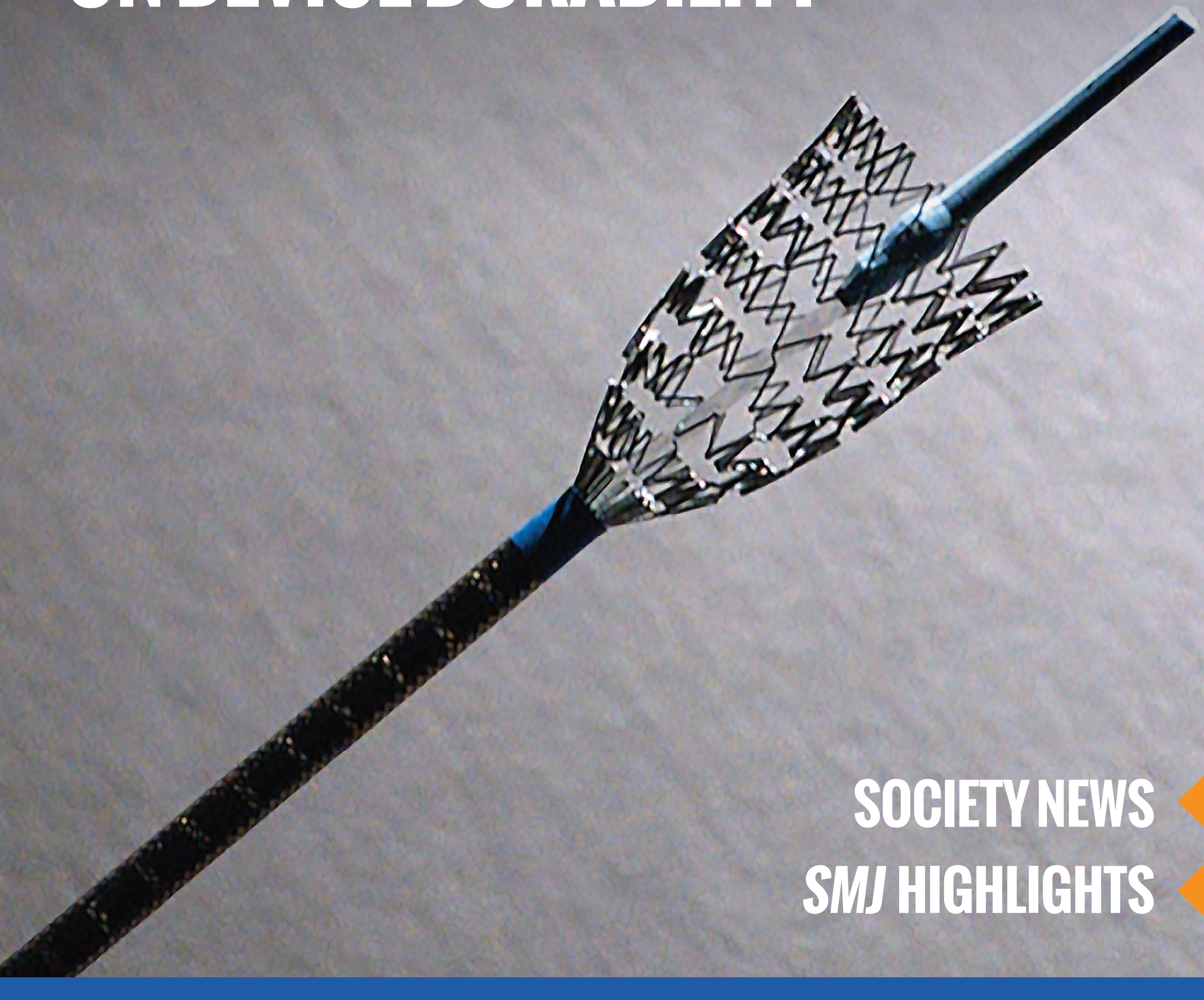
EFFECT OF NITINOL MICROPURITY ON DEVICE DURABILITY



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AN OFFICIAL PUBLICATION OF THE INTERNATIONAL ORGANIZATION ON SHAPE MEMORY AND SUPERELASTIC TECHNOLOGIES

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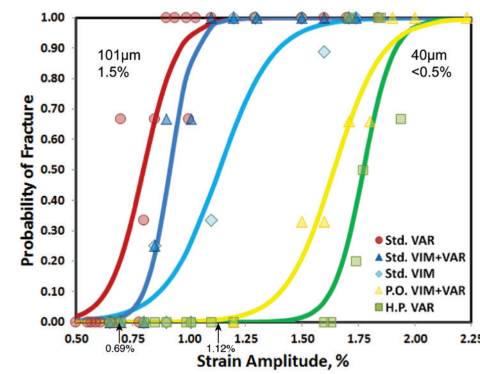

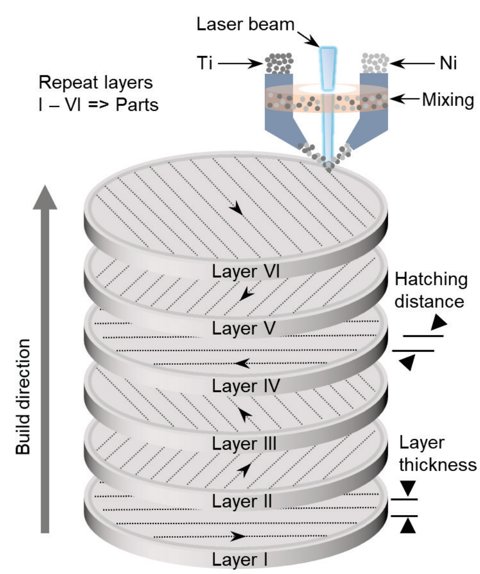

DEPARTMENTS

ABOUT THE COVER

Cordis SMART self-expanding stent manufactured from Nitinol shape memory alloy. Courtesy of Alan R. Pelton, FASM.

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SMST MEMBERS: THE PRIMARY BENEFIT

Benafan

In this unprecedented time, we wish all SMST members and their families good health and happiness. As many of us are working from home and no longer interacting with coworkers and lab mates day-to-day, we want to let you know you can still be around your SMST network. As a member, you have free access to our celebrated journal to keep you abreast of the latest publications in the field. You can read SMST conference proceedings to reexamine that must-have datapoint only gained at our face-to-face meetings. You can stay in touch with society happenings by reviewing our newsletters, social media platforms, and the CareerHub.

Most importantly, you have a connection to *people,* the thing that most of us urgently need, particularly in these unprecedented times. As a member, you have access to the SMST membership directory, linking you to a global network of SMST experts. Make sure you take advantage of this and don't forget about the old fashioned way to communicate with your colleagues—pick up the phone or send a quick note to collaborate, ask those burning questions, or simply just say hello. In addition, the officers and board members welcome your direct communication and we are eager to hear from you.

Speaking of society happenings, in this issue of the *SMST NewsWire* we bring you timely news and selected articles we hope you will enjoy. Whether or not your line of work entails medical devices, we can all agree that understanding fatigue behavior of high purity Nitinol for medical implants—the first featured article—is indisputably vital. And if medical devices are not your trade, fatigue of SMA actuators or SMAs in general can also benefit from the implications of high purity alloys and associated trends. In the past few years, we have also witnessed a surge in additive manufacturing and concepts related to elastocaloric effects. How about combining both technologies? The second featured article describes recent efforts to develop elastocaloric cooling material using 3D printed NiTi. We can all use new and more efficient refrigeration and HVAC systems in our homes. So take a look. These topics and more will be further highlighted in the upcoming SMST 2021 conference to take place May 17-21 in San Diego. We have already secured distinguished keynote speakers and panelists from all over the world. This conference also commemorates the 60 years of Nitinol, and we are preparing very special programming and *new* awards that you can't miss. So polish those last minute abstracts and mark your calendars.

Finally, the year 2020 marks the five-year anniversary of our *Shape Memory and Superelasticity* journal. I would like to thank the journal editor, associate editors, editorial board and staff, and most importantly the authors and reviewers whose reputable contributions make this journal a reality. I hope you enjoy this issue of *SMST NewsWire* and stay safe.

I look forward to seeing you "in-person" soon!

Othmane Benafan, Ph.D.
SMST '21 Chair
President, International Organization on
Shape Memory and Superelastic Technologies

SMST ANNOUNCES NEW OFFICERS AND BOARD MEMBERS

The Shape Memory & Superelastic Technologies (SMST) board, at the recommendation of the SMST Awards and Nominations Committee, named new officer **Adrian McMahon** to serve on the SMST Board for the 2020-2022 term as vice president/finance officer. Reappointed are **Othmane Benafan** (president) and **Jeremy Schaffer** (immediate past president) to serve on the SMST Board for the 2020-2022 term. New members are **Ashley Buscek** and **Jochen Ulmer** to serve on the SMST Board for the 2020-2023 term; reappointed is **Parikshith Kumar** to serve on the SMST Board for the 2020-2023 term. **Faith Gantz** will serve as Student Board Member for a one year term 2020-2021. Continuing on the board as members are **Frederick Calkins, Tom Duerig, Aaron Stebner, Andreas Undisz,** and **Martin Wagner.** Retiring from the board is Julianna Abel. Alan Pelton and Darel Hodgson will continue to be advisors on the board.

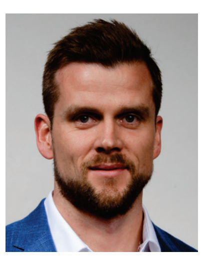
Adrian McMahon is a principal R&D engineer, currently working for Boston Scientific in Galway, Ireland. With over 15 years' experience working in the MedTech industry, McMahon's interest in shape memory alloys was sparked during his time working on the SADRA/BSC acquisition where he transitioned into the Structural Heart R&D Materials group, working on the development of next-generation, high cycle fatigue Nitinol wire for use in TAVR heart valves. McMahon now works as the Structural Reliability team lead for Structural Heart in Galway, as well as technical lead for the LOTUS Mantra next-generation valve development. He first got involved with SMST when asked to help organize a local MedTech focused SMST event in Galway, Ireland in May 2019, and later that year was appointed to the board of directors, where he continues to serve.

Ashley Buscek is an assistant professor in the Department of Mechanical Engineering at the University of Michigan. She received her M.S. and Ph.D. in mechanical engineering from the Colorado School of Mines (2018) where her research was supported by an NSF Graduate Research Fellowship and the NASA Glenn Research Center. She was a President's Postdoctoral Fellow in the Aerospace Engineering and Mechanics Department at the University of Minnesota (2018-2019) and a visiting scientist at the European Synchrotron Radiation Facility (2017). Her expertise lies in studying the relationships between micromechanics and macroscopic behavior in structural and functional materials using in situ three-dimensional x-ray characterization techniques. Some of her current interests include the mechanical behavior of microarchitectured shape memory alloys, twin nucleation in hcp metals, and titanium alloys during mechanical loading at high temperatures.

Faith Gantz is a master's/Ph.D. student of materials science and engineering at the University of North Texas. Gantz returned to higher education in the Dallas area with a desire to pursue art conservation. After being introduced to materials science, she developed an interest in shape memory alloys (SMAs). Gantz has collaborated with the Dallas Museum of Art Ceramic and Metal Work Collection and the Forging Foundation, working on high-entropy alloy (HEAs) research in Dr. Marcus L. Young's research group. The laser coating HEAs research earned her a Charles W. Finkl Scholarship sponsored by the Forging Industry Educational and Research Foundation. Her master's thesis and Ph.D. work on SMAs received support from the NASA ULI program. She also interned at the NASA Glenn Research Center. As an undergraduate, Gantz presented research on the effects of Ni in NiTiHf SMAs during thermomechanical processing at SMST 2019, winning 2nd place in the poster competition.

McMahon

Benafan



Schaffer

Buscek

Ulmer

Kumar

Gantz

Calkins

Duerig

Stebner

Undisz

Wagner

SMST MEMBERS NAMED 2020 ASM FELLOWS

SMST is pleased to announce that two of its members have joined the newest Class of Fellows. Congratulations to both members!

2020 Class of ASM Fellows

Mr. Luis Leon, FASM
Associate Technical Fellow
The Boeing Company
Seattle

"A materials technology expert and mentor who pioneered utilization of advanced materials and processes to improve the performance of high temperature commercial aircraft propulsion support systems."

Dr. Virginia Osterman, FASM
Senior Scientist
Solar Atmospheres, Inc.
Souderton, Pennsylvania

"For significant technical and educational contributions specific to vacuum heat treating processes, including use of vacuum furnaces for the embrittlement of titanium, tantalum and other refractory metals for powder production."

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Shape Memory & Superelastic Technologies
ASM INTERNATIONAL

SEEKING APPLICATIONS FOR SMST FOUNDERS' GRANT

The International Organization on Shape Memory and Superelastic Technologies (SMST), an affiliate society of ASM International, is seeking applications for the 2021 SMST Founders' Grant. The intent of the SMST Founders' Grant is to provide funding for early, exploratory research related to shape memory and superelasticity. It is expected that the funds will be used as a "seed grant," used to test a concept and lay a foundation for obtaining further funding from industry or government agencies. The grant, which was endowed in 2019 by Dr. T. W. Duerig, FASM, includes a stipend up to $50,000 over two years. **Deadline to apply is January 15, 2021**. For more information visit https://www.asminternational.org/web/smst/smst-fellowship or contact carrie.wilson@asminternational.org.

SMJ CELEBRATES FIFTH ANNIVERSARY

This year, ASM International is celebrating the fifth anniversary of the journal *Shape Memory and Superelasticity.* Throughout its existence, the journal has enjoyed the professionalism, dedication, and hard work of the same editor-in-chief and associate editors.

Prior to the journal's launch in 2015, founding editor-in-chief **Huseyin Sehitoglu, FASM,** University of Illinois at Urbana-Champaign, assembled a team of seven highly regarded associate editors. Under Professor Sehitoglu's leadership, this editorial team has supported *Shape Memory and Superelasticity* since its first issue and continues to do so!

The journal's associate editors are:

Tom Duerig, FASM, Nitinol Devices & Components Inc., Fremont, California, USA

Dimitris Lagoudas, Texas A&M University, College Station, USA

Yinong Liu, The University of Western Australia, Crawley

Hans Jurgen Maier, Leibniz Universität Hannover, Garbsen, Germany

Shuichi Miyazaki, University of Tsukuba, Japan

Petr Sittner, Academy of Sciences of the Czech Republic, Prague

Thomas Waitz, University of Vienna, Austria


Sehitoglu


Duerig


Lagoudas


Liu


Maier


Miyazaki


Sittner


Waitz

THE INFLUENCE OF NITINOL 'MICROPURITY' ON MEDICAL IMPLANT DURABILITY

The effects of Nitinol micropurity on the durability of superficial femoral artery stents offers a potential way to enhance durability and reduce fatigue fractures.

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J. Ulmer, K. Plaskonka,* and A. Keck,* G.Rau GmbH, Pforzheim, Germany*

M.R. Mitchell, FASM, Mechanics and Materials Consulting LLC, Flagstaff, Arizona*

P. Saffari, Engage Medical Device Services Inc., Newport Beach, California*

Cardiovascular implants such as stents, stent grafts, heart valve frames, and *vena cava* filters are designed to function for the lifetime of the patient. As part of the approval process for these life-saving implants, the USFDA requires durability assessment of peripheral implants for a minimum of ten years that results in 380 million cycles of deformation from cardiac pulsatility, musculoskeletal motions of up to 10 million cycles[1], and an additional 100 million respiratory cycles[2]. Over the past two decades, Nitinol stents have demonstrated superior clinical outcomes for treatment of peripheral arterial disease (PAD) compared with conventional balloon angioplasty alone[3]. Although the use of Nitinol stents has been quite successful for treatment of PAD, *in vivo* fractures and failures have been reported during follow-up procedures[4]. A summary overview article on superficial femoral artery (SFA) stenting conducted at the USFDA commented that stents still fracture at a measurable rate although improvements have been made to significantly improve their durability[4]. As such, recent efforts in Nitinol stenting have focused on the essential task of improved understanding of the biomechanics[5] in the diseased vessel and improved designs and material response to withstand more severe *in vivo* deformations, such as axial compression and bending.

In parallel with these activities, there has been a concerted effort to improve the Nitinol metallurgy, specifically the characteristics and importance of nonmetallic inclusions, to improve *in vivo* stent durability. The vast majority of commercially available SFA Nitinol stents referred to in the USFDA study[4] were manufactured from "standard-grade" Nitinol. Therefore, the purpose of this article is to highlight recent work on superior grades of "microclean" Nitinol and the effects on fatigue and durability of the devices.

EFFECT OF NITINOL MICROPURITY ON DEVICE DURABILITY

Several recent publications addressed the effects of nonmetallic inclusions on Nitinol fatigue[6-9]. These investigations demonstrate conclusively that inclusions and the adjacent voids are internal defects and act as potent initiation sites for fatigue cracks. The investigation by Robertson et al.[7] offers the most comprehensive study to date on the effects of inclusion type and content on Nitinol fatigue under two modes of cyclic deformation. In the Robertson et al. study, superelastic wires (ø0.25mm) and diamond-shaped stent surrogates (processed from ø8mm tubing) were tested from five different mill product suppliers. Test specimens were processed to obtain a transformation temperature of 20°C and were tested in a 37°C water bath with 6% pre-strain (equivalent stent crimp strain), 3% mean strain (equivalent stent oversizing strain), with a range of strain amplitudes (equivalent stent cyclic conditions). These test conditions simulate typical *in vivo* environments, whereby fatigue cycling is conducted on the unloading plateau to 10 million cycles.

Figure 1 shows the fatigue fracture probability as a function of strain amplitude for the diamond specimens for all five

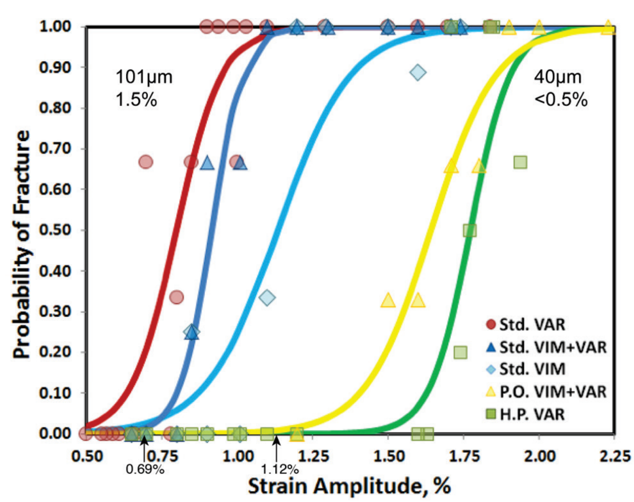

Fig. 1 — Probability of Nitinol diamond fracture at 10M cycles versus strain amplitude plots with a logit sigmoidal curve fit line for the five Generation I and II Nitinol materials. The maximum inclusion length and inclusion area fraction for the VAR I and VAR II materials measured from the finished device are shown. Reprinted from Robertson et al.[7] with permission from Elsevier.

**Member of ASM International*

Nitinol materials[7]. This figure is quite revealing and demonstrates that not all Nitinol material is the same with respect to fatigue properties. A logistic statistical analysis was conducted to determine the most probable factors to explain these results. Among the factors considered were microscopic stress concentrators (inclusion length and location, and grain size), probabilistic factors (area fraction of inclusions), and macro-mechanics (transformation temperature, upper and lower plateau stress, strain amplitude, mean strain, test temperature). The model that most accurately represented the experimental data contained inclusion length, density of inclusions, and strain amplitude. Of these variables, because strain amplitude is a test condition control variable and not a material characteristic, the effects of inclusions are the most dominant factors to influence the prediction of fatigue behavior. Furthermore, the influence of inclusion length was four times greater than that of inclusion density to predict fatigue fracture. For example, in Fig. 1 the Nitinol material with the lowest fatigue strain limit has a device maximum inclusion length of 101 µm, whereas, the material with the greatest fatigue strain limit in this study has an inclusion length of only 40 µm. This investigation also demonstrated that the effects of inclusion length (measured on the finished device) were more pronounced under cyclic bending conditions compared with the uniaxial tension-tension cycling. This difference is likely due to the amount of deformed volumes (outer surfaces in bending and entire cross section in axial) and the probability of an inclusion located in the high-strain region.

These results afford great insight into the potential benefits of even greater purity microstructures, such as those observed in electron beam remelted (EBR) Nitinol. A recent study[9] compared the fatigue response of EBR Nitinol with other high-purity Nitinol with diamond coupons, similar to those in Robertson et al.[7]. Diamonds were processed from 10 mm OD x 0.53 mm wall thickness tubing to a transformation temperature of 20°C. Testing was conducted at 37°C with a crimp strain of 6%, mean strain of 5%, and a range of strain amplitudes to 10 million cycles. The results of these tests are shown in Fig. 2a and confirm that the two high-purity materials from the Robertson et al. paper have comparable fatigue behavior. The EBR Nitinol fatigue data illustrates an enhanced 10 million-cycle fatigue strain limit (~1.9%) based on testing from 13 diamond lots, two coupon manufacturing vendors, and from five ingots. Figure 2b-d shows representative microstructures of the three high-purity Nitinol materials in Fig. 2a from the longitudinal direction from the diamond coupon test specimens. The darker gray particles are oxide inclusions that form in the melt process; some of the particles in Fig. 2b are

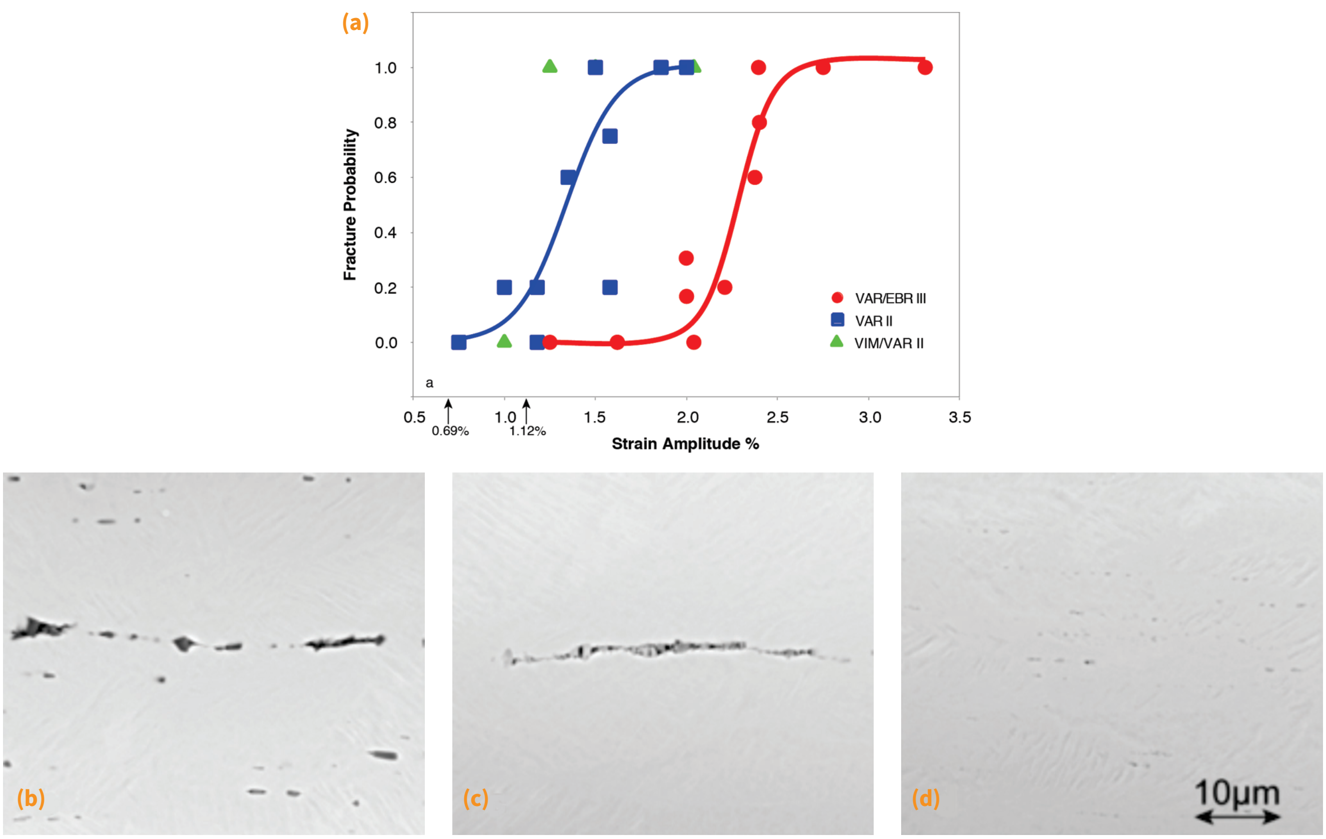

Fig. 2 — (a) Probability of Nitinol diamond fracture at 10 million cycles versus strain amplitude plots for Generation II VAR, Generation II VIM/VAR and Generation III VAR/EBR. (b) Generation II VIM/VAR microstructure showing a ~40 µm long oxide inclusion along with a mixture of smaller oxide and carbide particles. (c) Generation II VAR microstructure showing a ~40 µm long oxide inclusion “stringer” with voids. (d) Generation III VAR/EBR microstructure showing a dispersion of ≤ 5 µm oxide inclusions. After Pelton et al.[9].

TABLE 1 – SUMMARY OF COMMERCIALLY AVAILABLE NITINOL[9]

Material Classification	Year Introduced	Melt Source*	Conforms to ASTM F2063	Maximum Device Inclusion Size (μm)	Device Inclusion Area Fraction, %	Reference
Generation I	*ca*. 1990	VAR I VIM/VAR I	Yes	101	1.5	7
Generation II	*ca*. 2005	VAR II VIM/VAR II VIM	Yes	20-50	0.41-2.67	7, 9
Generation III	*ca*. 2010	VAR/EBR III	Yes	<5	<0.5	9

*VAR = Vacuum Arc Remelt; VIM = Vacuum Induction Melt; EBR = Electron Beam Remelt

carbides due to the melt practice in a graphite crucible. The EBR oxide inclusions have dimensions < 10 μm in the longitudinal direction. A recent presentation summarized the evolution in commercially available Nitinol and is presented in Table 1[9]. This table illustrates that the more recent Nitinol tends to have shorter inclusions and lesser inclusion area fraction in the final device. The decreased particles size produced by the EBR process leads clearly to enhanced fatigue behavior at longer fatigue lifetimes.

IMPLICATIONS FOR MEDICAL IMPLANT DURABILITY

Saffari[10] conducted finite element analysis (FEA) with a generic Nitinol self-expanding stent model and applied cyclic axial compression and bending deformations according to deformations considered for the SFA environment[4]. Application of an axial compression of 8.6% on this stent results in a mean strain of 3.9% with a corresponding strain amplitude of 0.69%, whereas, a 22.6 mm bending radius results in 5.6% mean strain and 1.12% strain amplitude. To illustrate how these stent strain amplitudes can be analyzed with the fatigue probability, arrows to mark the strain amplitudes are shown on Figs. 1 and 2. The strain amplitude due to cyclic axial compression exceeds the 10 million-cycle fatigue strain limits for Generation I Nitinol, which could explain the high fracture rates for Nitinol SFA stents[4]. If we consider the 1.12% strain amplitude due to cyclic bending, fatigue fractures would be expected in both Generation I materials and the VIM Generation II Nitinol. Figure 2 shows that if these stents are instead manufactured from Generation II or Generation III Nitinol, the probability of fracture would be reduced significantly. In fact, the fatigue safety factor for these bending conditions with Generation III Nitinol is 1.9%/1.12% > 1.6, confirming the low probability of fatigue fracture under extreme *in vivo* conditions.

This article focused on the effects of Nitinol "micropurity" on the durability of SFA stents and offers a potential way to enhance durability and reduce fatigue fractures. In addition, it is expected that Generation II and especially Generation III Nitinol will be beneficial for use in even more challenging anatomies, such as heart valve repair and replacement frames. The strains in such environments may be significantly greater than those in the femoral artery and therefore, these improved Nitinol materials are expected to increase device durability. **~SMST**

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A BREAKTHROUGH IN SOLID-STATE COOLING ABILITIES OF SHAPE MEMORY ALLOYS ENABLED BY 3D PRINTING

Laser melting of elastocaloric metals can create fatigue-resistant microstructures, which enables solid-state cooling technologies.

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Huilong Hou, Beihang University, Beijing, P.R. China
Ichiro Takeuchi, University of Maryland, College Park

A collaborative team of researchers led by Ichiro Takeuchi and Huilong Hou of the University of Maryland (Hou is now an assistant professor at Beihang University, Beijing, China), together with colleagues from Iowa State University, Ames National Laboratory, and Colorado School of Mines, developed and demonstrated that 3D printed nickel-titanium (NiTi, trade name Nitinol) shape memory alloys (SMAs) can attain better solid state cooling performances than the best performances known of traditionally manufactured SMAs. Specifically, the 3D printed materials showed 20 to 30 % less normalized energy lost without failing to over 1 million cycles relative to energy that is lost by conventionally processed NiTi materials in 100,000 cycles (Fig. 1a). The initial study was published in *Science*[1].

ELASTOCALORIC COOLING

Cooling technology, used in refrigeration and HVAC systems around the globe, is a multi-billion dollar business[2]. Vapor compression cooling, which has dominated the market for over 150 years, has not only plateaued where efficiency is concerned, but also uses chemical refrigerants with high global-warming potential (GWP). Solid-state elastocaloric cooling, where stress is applied to materials to release and absorb (latent) heat, has been under development for the last decade and is a frontrunner among the so-called “alternative” cooling technologies[3]. Shape-memory alloys are found to display a significant elastocaloric cooling effect; however, presence of hysteresis—work lost in each cycle and cause of functional fatigue and eventual failure—remains an open challenge.

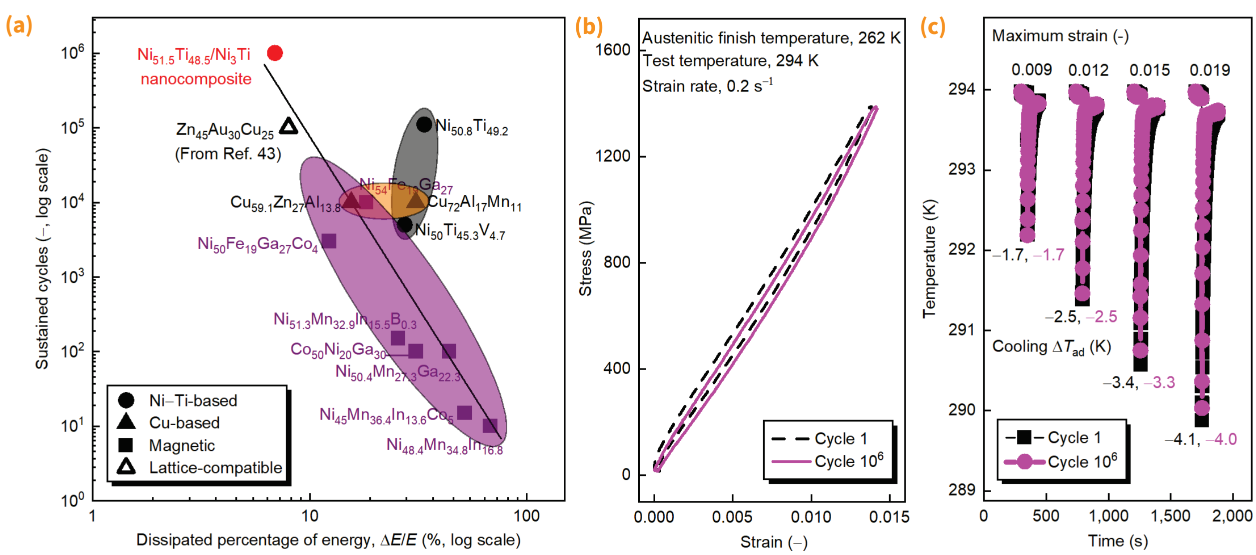

Fig. 1 — (a) 3D printed NiTi/Ni_3Ti nanocomposite materials (red) showed an order of magnitude improvement in lifetime together with greater energy efficient (lower energy lost (Δ*E*) normalized by the total energy (*E*)) during elastocaloric cycling, relative to the best performing elastocaloric and magnetocaloric SMAs made using traditional processing methods. The 3D printed materials were also highly resistant to functional fatigue that often plagues SMAs in applications, as demonstrated by (b) the mechanical response of cycle 1,000,000 being nearly identical to the mechanical response of cycle 1 for the greatest cyclic loading used in the study, and (c) the elastocaloric performances of cycle 1,000,000 being nearly identical to cycle 1 for several different temperature intervals (Δ*T*). Reproduced from Hou et al.[1] with permission.

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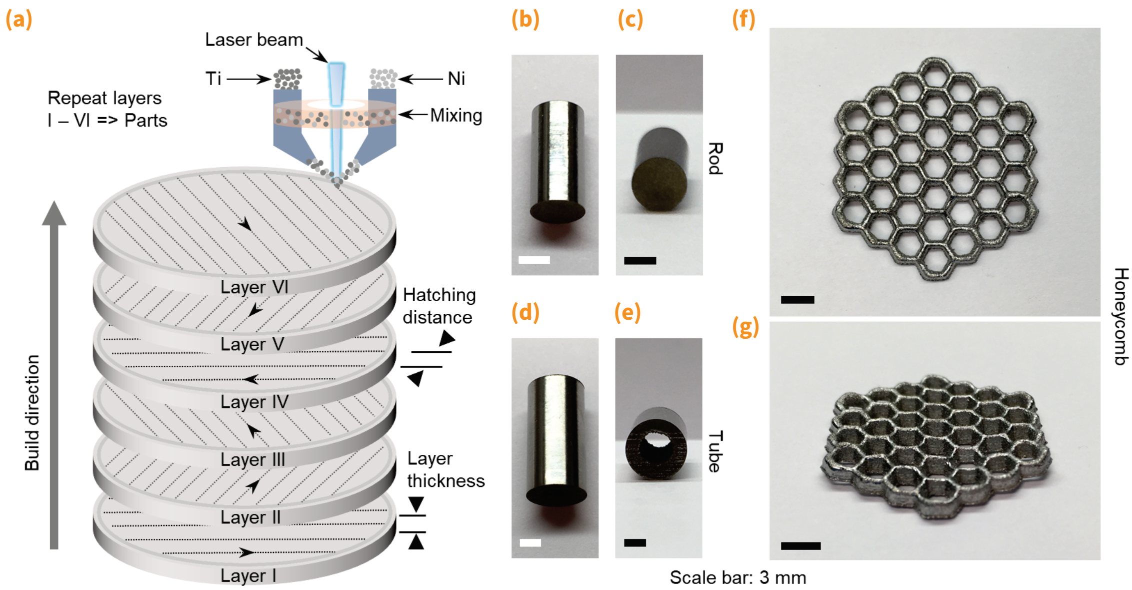

Fig. 2 — In a 3D printing, or more accurately, additive-manufacturing process, material is deposited in a sequential, layer-wise manner and fabricated directly into the (near) final part geometry. In this study, the laser directed energy deposition (DED) 3D printing technology was used, also known as laser engineered net shaping, or LENS. (a) In this process, powders are blown through a nozzle into the focal point of a laser and melted onto a substrate by the laser. A computer numerical control (CNC) bed manipulates the substrate beneath the laser in a path that forms the desired part geometry. The direction of the deposition path may be alternated in subsequent layer to improve the isotropy of the material performance in the final part geometry. Simple geometries such as (b-c) rods and (d-e) tubes may be fabricated, in addition to more complex geometries such as (f-g) honeycombs, which for solid-state cooling technologies, can be optimized to improve heat exchange between the elastocaloric SMA and its surrounding environment. Adapted from Hou et al.[1] with permission.

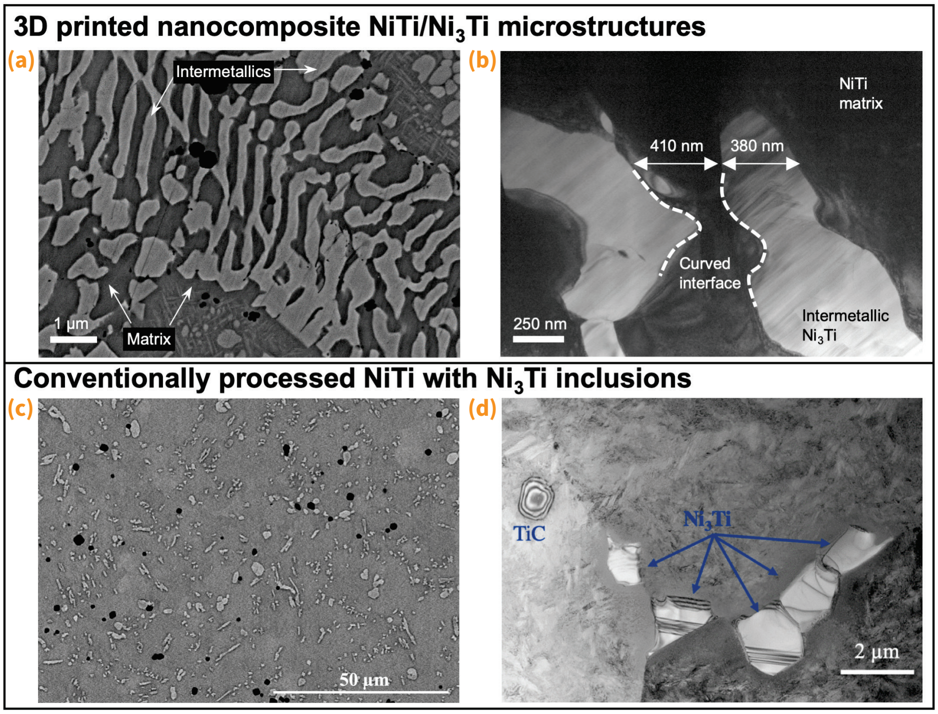

Fig. 3 — Using the laser-DED 3D printing technology to process blended Ni and Ti powders resulted in (a-b) nanocomposite microstructures composed primarily of NiTi and Ni_3Ti phases. The curved, well dispersed nature of the nanocomposite interfaces serves to strengthen the material against fatigue, and also limits the hysteresis. Normally, using conventional processing methods, (c) Ni_3Ti phase forms as more heterogeneously distributed micro-inclusions, (d) often concentrated at grain boundaries, which promotes fracture and limits the cyclic performance. Figures a and b reproduced with permission from Hou et al.[1] and Figs. c and d reproduced from Benafan et al.[7] with permission.

To that end, an improved elastocaloric cooling material was developed by blending nickel and titanium metal powders together, forged using a 3D printer (see Fig. 2). The new material is more efficient than current SMA technology and is also a significantly more "green" cooling technology than the commercial technologies available today. Moreover, it can be quickly scaled up for use in larger devices.

FATIGUE-RESISTANT MICROSTRUCTURES

Comparatively speaking, there are three classes of caloric cooling technology–magnetocaloric, electrocaloric, and elastocaloric–all of which are "green" and vapor-less[4-6]. Magnetocaloric, the oldest of the three, has been under development for 40 years and is just now on the verge of being commercialized. Some magnetic SMAs are also the leading elastocaloric materials. However, to date, their lifetimes in cooling applications have been limited to several thousand cycles at best (Fig. 1a). The breakthrough in the ability for the 3D printed NiTi to sustain more than a million elastocaloric cycles extends the potential life of a refrigerator out to ten years or more, leading to commercial viability. Moreover, the 3D printed NiTi material showed performances that were robust to functional fatigue, which often plagues the adoption of SMA technologies. Functional fatigue describes the degradation of the performance of the material, even though the material itself remains structurally intact. For elastocaloric materials, functional fatigue is exhibited in two ways: 1) the mechanical stress-strain, or the "elasto" part of the performance, changes with cycling, and 2) the heat exchange time-temperature, or "caloric" part of the performance, degrades with cycling. As shown in Fig. 1b-c, the 3D printed NiTi material resisted both types of degradation.

The reason the 3D printed materials perform better is that a secondary non-SMA phase, specifically a Ni_3Ti intermetallic phase, forms in well dispersed, wavy nanostructures amongst the NiTi SMA phase during 3D printing, as shown in Fig. 3a-b. This nanocomposite, two-phase microstructure strengthens the alloys to degradation while also improving thermal efficiencies during elastocaloric cycles. The local processing of material in a 3D printing process allows these special structures to form. While the same phase can form in conventionally processed SMAs, these structures have not been previously observed. In fact, when these same phases are formed via conventional processing, where an entire ingot of material is thermomechanically processed at once, the structures are typically one to tens of micron sized inclusions that are detrimental to the performances of conventionally processed SMAs (Fig. 3c-d[7]). In the 3D printing process, the rapid, localized heating and cooling of molten material limits these phases from coalescing and growing into the conventionally attained larger, detrimental structures.

In addition to the metallurgical advancement, the 3D-printing process also provides opportunities for transforming the mechanical engineering of solid-state cooling technologies. In elastocaloric cooling, the SMA material functions as both the refrigerant and the heat exchanger. 3D printing provides the ability to manufacture the material into advanced, topology optimized heat exchanger geometries that are otherwise too expensive or even impossible to make with traditional forming and machining processes, as demonstrated in Fig. 2f-g. Hence, in addition to the improved material performance, this new technology also provides for better cooling performances via new and improved designs of the heat exchange devices. ~SMST

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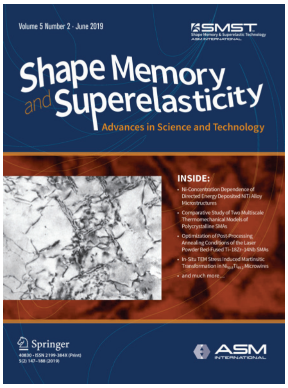


Shape Memory and Superelasticity: Advances in Science and Technology (*SMJ*) is the official journal of the International Organization on Shape Memory and Superelastic Technologies (SMST), an affiliate society of ASM International. The journal publishes original peer-reviewed papers that focus on shape memory materials research with contributions from materials science, experimental and theoretical mechanics, physics with cognizance of the chemistry, underlying phases, and crystallography. It also provides a forum for researchers, scientists, and engineers of varied disciplines to access information about shape memory materials. The four articles described here are from the June issue, which contained papers honoring Professor Gunther Eggeler for 25 years of shape memory research. All were selected by *Shape Memory* Editor-in-Chief Huseyin Sehitoglu. *SMJ* is available through springerlink.com. For more information, visit asminternational.org/web/smst.

THE EFFECT OF INCREASING CHEMICAL COMPLEXITY ON THE MECHANICAL AND FUNCTIONAL BEHAVIOR OF NiTi-RELATED SHAPE MEMORY ALLOYS

Christian Hinte, Khemais Barienti, Jan Steinbrücker, Jana-Mercedes Hartmann, Gregory Gerstein, Sebastian Herbst, David Piorunek, Jan Frenzel, Andrea Fantin, and Hans Jürgen Maier

The introduction of high-entropy alloys (HEA) into the field of shape memory alloys offers enormous potential for improving their functional properties. It is shown how a successive increase in chemical complexity results in strictly monotonically enlarged and increasingly distorted lattices. With increasing the number of elements added to the alloy, the effect of solid solution strengthening appears to be curtailed and first insights into the contribution of additional mechanisms based on lattice distortions are possible. The alloys developed in this study, reaching from ternary NiTiHf to senary TiZrHfCoNiCu, show a great potential to exploit interatomic interactions regarding improvement of functional fatigue. Despite the absence of stress plateaus related to detwinning, recovery effects at loads above 1000 MPa and significant strain recoveries are shown (Fig. 1).

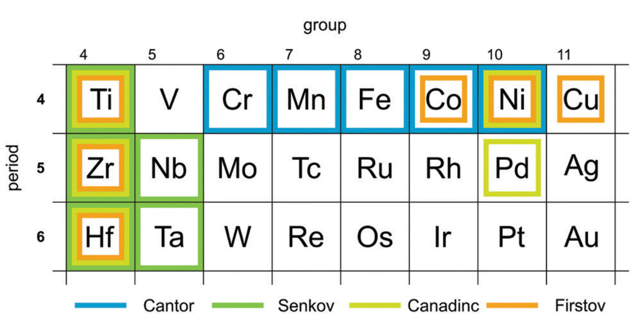


Fig. 1 — Excerpt from the periodic table of elements; alloy systems investigated by the different research groups are highlighted by the respective color.

DSC CYCLING EFFECTS ON PHASE TRANSFORMATION TEMPERATURES OF MICRON AND SUBMICRON GRAIN $Ni_{50.8}Ti_{49.2}$ MICROWIRES

Saeid Pourbabak, Bert Verlinden, Jan Van Humbeeck, and Dominique Schryvers

The effect of thermal cycling parameters on the phase transformation temperatures of micron and submicron grain size recrystallized Ni–Ti microwires was investigated. The suppression of martensitic transformation by thermal cycling was found to enhance when combined with room temperature aging between the cycles and enhances even more when aged at elevated temperature of 100°C. While aging at room temperature alone has no clear effect on the martensitic transformation, elevated temperature aging at 100°C alone suppresses the martensitic transformation. All aforementioned effects were found to be stronger in large grain samples than in small grain samples. Martensitic transformation suppression in all cases was in line with the formation of Ni_4Ti_3 precursors in the

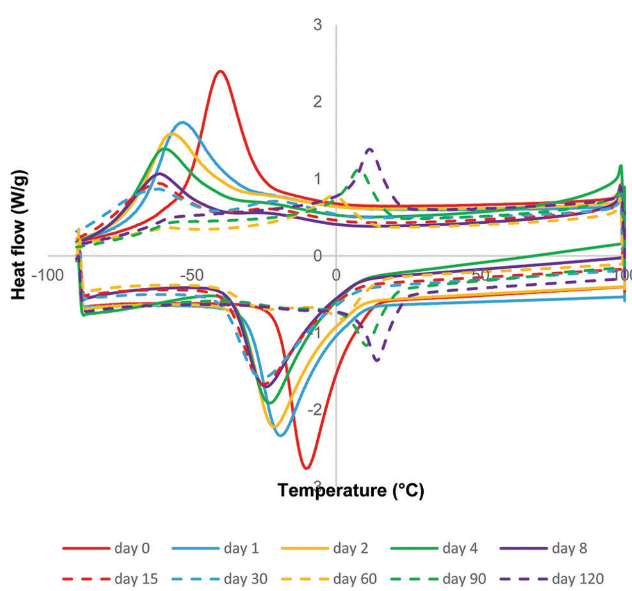


Fig. 2 — DSC results of the LEC sample tested at different days and aged at 100°C in between.

form of $\langle 111 \rangle_{B2}$ Ni clusters as concluded from the observed diffuse intensity in the electron diffraction patterns revealing short-range ordering enhancement. Performing thermal cycling in some different temperature ranges to separate the effect of martensitic transformation and high temperature range of differential scanning calorimetry cycling revealed that both high temperature- and martensitic transformation-included cycles enhance the short-range ordering (Fig. 2).

FUNCTIONAL AND STRUCTURAL FATIGUE OF PSEUDOELASTIC NiTi: GLOBAL VS. LOCAL THERMO-MECHANICAL RESPONSE

Franco Furgiuele, Pietro Magarò, Carmine Maletta, and Emanuele Sgambitterra

Functional and structural fatigue properties of a pseudoelastic NiTi alloy were analyzed at the light of local non-homogenous thermo-mechanical response, resulting from Lüder's-like transformation bands. To this aim, in-situ full-field strain and temperature measurements were made during fatigue tests. Structural and functional fatigue damage phenomena were studied by analyzing the evolutions of strains and temperature at the sample scale as well as within the transformation bands. Marked losses in the pseudoelastic recovery capabilities were recorded, mainly occurring in the first loading cycles, leading to material stabilization after about 200 cycles. Very large differences between the two scales were observed, that is, reduction of pseudoelastic recovery at the global scale is attributed to the accumulation of residual deformation in the transformation bands. These local effects tend to vanish for strains beyond the stress-induced transformation regime, due to the saturation of martensitic bands. The effects of local deformations on the structural fatigue properties, in terms of strain-life curves, were also analyzed. It was demonstrated that localized strains play a very important role on the evolution of structural damage, especially within the pseudoelastic regime of the alloy, and they represent the key to understand unusual strain-life curves at the global scale (Fig. 3).

ON THE IMPORTANCE OF STRUCTURAL AND FUNCTIONAL FATIGUE IN SHAPE MEMORY TECHNOLOGY

Jan Frenzel

This article provides a brief overview on structural and functional fatigue in shape memory alloys (SMAs). Both degenerative processes are of utmost technological importance because they limit service lives of shape memory components. While our fundamental understanding of these two phenomena has improved during the last two decades, there are still fields which require scientific attention. NiTi SMAs are prone to the formation of small cracks, which nucleate and grow in the early stages of structural fatigue. It is important to find out how these micro-cracks evolve into engineering macro-cracks, which can be accounted for by conventional crack growth laws. The present work provides examples for the complexity of short crack growth in pseudoelastic SMAs. The importance of functional fatigue has also been highlighted. Functional fatigue is related to the degeneration of specific functional characteristics, such as actuator stroke, recoverable strain, plateau stresses, hysteresis width, or transformation temperatures. It is caused by the accumulation of transformation-induced defects in the microstructure. The functional stability of SMAs can be improved by (1) making phase transformations processes smoother and (2) by improving the material's resistance to irreversible processes like dislocation plasticity. Areas in need of further research are discussed (Fig. 4 on next page).

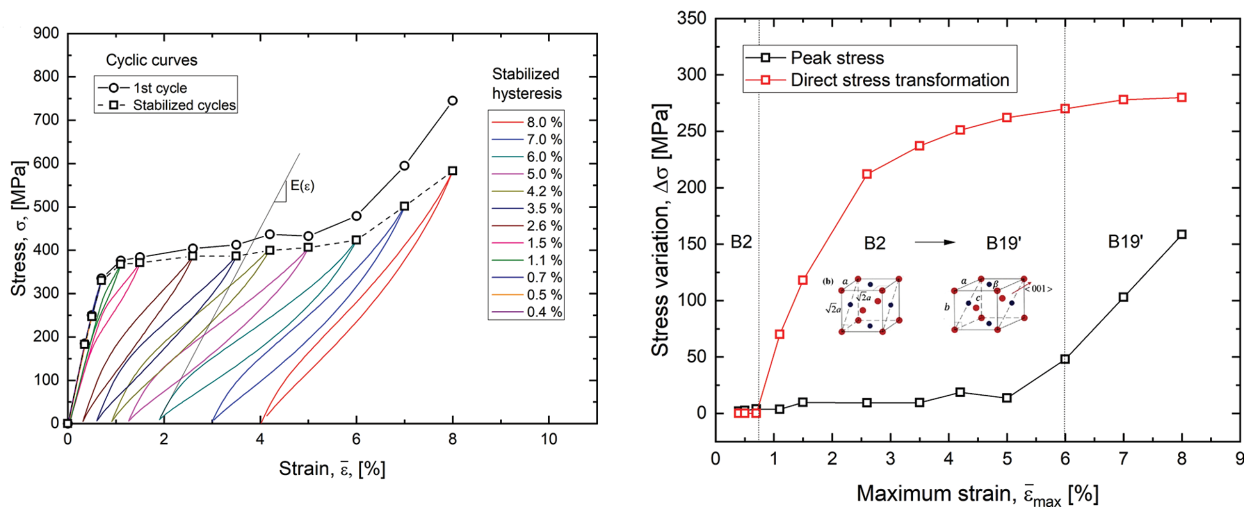


Fig. 3 — Cyclic evolution of the stress–strain response at the global scale: (a) stabilized hysteresis cycles at different maximum strain and cyclic curves; (b) variation of the peak and transformation stresses after material stabilization with respect to the first cycles.

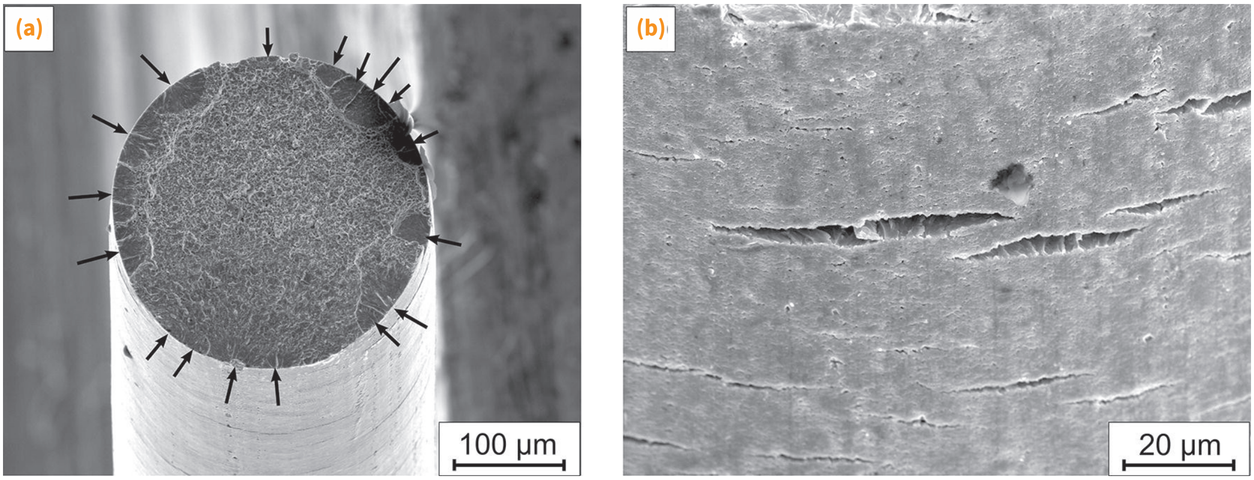


Fig. 4 — Coupled functional and structural fatigue of NiTi SMA wires: (a) Fracture surface with crack initiation sites indicated by arrows; (b) skin surface of the fractured wire showing high density of small micro-cracks.

ASMNEWS

ASM MATERIALS EDUCATION FOUNDATION ANNOUNCES 2020 SCHOLARSHIP WINNERS

William Park Woodside Founder's Scholarship

The William Park Woodside Founder's Scholarship was established in 1996 by a gift from Mrs. Sue Woodside Shulec in honor of her grandfather. William Park Woodside founded our Society as the Steel Treaters Club more than 100 years ago and later served as president of ASM. The scholarship was established to support an ASM student member studying materials science and engineering at the junior or senior level who demonstrates strength in leadership, character, and academics. Tuition of up to $10,000 for one academic year and a certificate of recognition are awarded to the recipient.

Hannah Walker

University of Wisconsin-Madison

Walker is entering her final year at the University of Wisconsin-Madison, studying materials science and engineering. She is emphasizing her studies in polymers and earning a certificate (minor) in international engineering. To Walker, materials engineering is an area that allows her to combine her math-and-science/heavy thinking style with her creative mindset. She has interned in various industries, including pharmaceuticals, aerospace, and medical devices. Most recently, she found her passion working in performance textile applications at W. L. Gore and Associates.

The Lucille and Charles A. Wert Scholarship

The Lucille and Charles A. Wert Scholarship was established in 2006 through a generous bequest by the couple. It serves as an expression of their commitment to education and the materials science and engineering community. Tuition of up to $10,000 for the academic year is awarded through this scholarship.

Jacob Maxwell Wall

University of Alabama-Tuscaloosa

Wall is a rising junior at the University of Alabama, where he majors in metallurgical and materials engineering. Maintaining a 4.0 GPA, Wall has worked since his freshman year under Dr. Feng Yan to enhance the efficiencies of carbon-based perovskite solar cells. He published a paper about his research, and won at the Undergraduate Research and Creative Activity conference. Although Wall accepted an internship with the US-ITER program, he was unable to participate due to the COVID-19 pandemic.

George A. Roberts Scholarships

The George A. Roberts Scholarships were established in 1995 through a generous contribution from Dr. George A. Roberts, FASM, past president and retired CEO of Teledyne, to the ASM Foundation as an expression of his commitment to education and the materials science and engineering community. Scholarships are awarded to outstanding undergraduate members of ASM at the junior or senior level who demonstrate exemplary academic and personal achievements, and interest and potential in metallurgy or materials science and engineering. Five scholars will receive a certificate and check for $6000 toward educational expenses for one academic year.

Robert Giebel

The University of Akron

Giebel is entering his fourth year in the corrosion engineering program at The University of Akron. In his junior year of high school, he completed a job shadow under a metallurgist at Ellwood Quality Steels and discovered that he loved what the field had to

ASM INTERNATIONAL
Submit news of ASM and its members, chapters, and affiliate societies to Joanne Miller, editor, ASM News | ASM International
9639 Kinsman Road | Materials Park, OH 44073 | P 440.338.5455 | F 440.338.4634 | E joanne.miller@asminternational.org
Contact ASM International at 9639 Kinsman Road, Materials Park, OH 44073 | P 440.338.5151 ext. 0 or 800.336.5152 (toll free in U.S. and Canada) | F 440.338.4634 | E MemberServiceCenter@asminternational.org | W asminternational.org

offer. Combined with his love of chemistry, corrosion engineering was the perfect fit for him. Giebel has interned with The Timken Co., working in both the research and development and metallurgy groups.

Jonathan Hollenbach

Drexel University

Hollenbach is a rising senior at Drexel University, majoring in materials science and engineering. At the Drexel Nanomaterials Institute, he synthesized novel MXene supercapacitors. He worked to help optimize high-temperature ceramic sintering at the Army Research Laboratory and presented his work as a speaker at ICACC'19. At Sartomer and Arkema Inc., he developed resin formulations for stereolithography 3D printing. Hollenbach is currently working with Drexel's Particulate Materials Group to design finite element analysis models for metal additive manufacturing.

Owen Murdock

The Ohio State University

At 16, Murdock developed a passion for welding after enrolling in a welding fabrication program. In high school, he pursued positions at Capital Steel and Worthington Industries. Murdock won several awards, including a national gold medal for public speaking and leadership skills at SkillsUSA. Currently a junior in welding engineering at OSU, his next goal is to intern in Germany and perform graduate research with a Ph.D. mentor in summer 2021.

Michael O'Neill

Georgia Institute of Technology

O'Neill is a senior at Georgia Tech, studying materials science and engineering with a structural and functional materials concentration. He was first introduced to the field of materials science in high school, when he attended an ASM Materials Camp at Drexel University. O'Neill has undertaken research related to metallographic sample preparation and microstructural characterization of thin copper films. He has interned at Laboratory Testing Inc. and NASA Langley Research Center, and is currently an intern for Lockheed Martin Space.

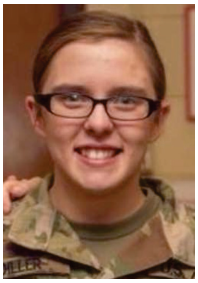
Anna Park

Carnegie Mellon University

Park is a senior at Carnegie Mellon, studying materials science and engineering with a minor in electronic materials. After a high school internship on perovskite solar cells at the University of Maryland, Park knew she wanted to pursue materials science in college and start research right away. She has interned at CEA/CNRS Néel in Grenoble, France, studying InAs nanowires used in quantum computing. She has also performed research on the characterization and growth of ohmic contacts on alloyed gallium oxide.

Acta Materialia Scholarships

The Acta Materialia Scholarships were established in 2017 by Acta Materialia through its Board of Governors, as an expression of commitment to education and the materials science and engineering community. Two scholars will each receive a certificate and check for $5000 toward educational expenses for one academic year.



Eden Diller

Trine University

Diller is a sophomore at Trine University, where she majors in chemical engineering with a minor in metallurgy. She has worked for New Millennium Building Systems LLC and Steel Dynamics Inc. as an environmental engineering co-op for two terms, focusing her attention on federal environmental reporting requirements and exploring process engineering in the metallurgy world. Diller was called up for active duty this summer with the Indiana National Guard for COVID-19 response. She is excited to resume her engineering curriculum.

Anastasia July

University of Pittsburgh

July is a senior at the University of Pittsburgh, studying materials science and engineering with a concentration in ferrous physical metallurgy. She plans to pursue a career in the steel industry as a metallurgist. During her sophomore and junior years, she worked with Pitt's ferrous physical metallurgy lab on microstructural analysis. July interned with Nucor Steel Decatur this past summer and enjoyed the industry experience working in the cold mill.

2020 SCHOLARSHIP WINNERS

David J. Chellman Scholarship

The David J. Chellman Scholarship was established in 2014 by Mrs. Arline Denny in honor of her husband, a long-standing Senior Technical Fellow with Lockheed Martin Corp. and ASM Life Member who enthusiastically served on the AeroMat Conference Organizing Committee for more than 25 years. The scholarship is an expression of his commitment to education and the materials science and engineering community, and is awarded based on academic merit and financial need. Tuition of $2500 for the academic year is awarded through this scholarship.

Max Bowman

Rice University

Bowman is a rising sophomore at Rice University, studying materials science and nanoengineering (MSNE) and physics. Since performing density functional theory research as a high school senior, he has been interested in using scientific computing to explore material properties. Bowman performs research in the Hazzard research group at Rice, where he studies the computational prediction of properties of dimerized fermion lattices. He recently interned at Argonne National Laboratory, writing software to make large-scale quantum system simulations more accessible.

Ladish Co. Foundation Scholarship

Established in 2011, the Ladish Co. Foundation Scholarship is awarded to an outstanding undergraduate member of ASM who has demonstrated exemplary academic and personal achievements, as well as interest and potential in metallurgy or materials science and engineering. (Student must be a Wisconsin resident and must attend a Wisconsin university to qualify.) One scholar was selected this year, and will receive a certificate and check for $2500 toward educational expenses for one academic year.

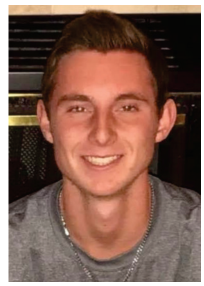
Baily Syring

University of Wisconsin-Madison

Syring is entering her senior year, majoring in materials science and engineering and minoring in German at the University of Wisconsin-Madison. Her fascination with metals started in her sophomore year, when she began doing research in the Thoma Lab in Wisconsin's Grainger Institute for Engineering. There, Syring researched the effect of hydrogen on steels and was introduced to additive manufacturing. She has worked as an intern for Collins Aerospace and Avient.

Outstanding Scholar Awards

The Outstanding Scholar Awards were established to recognize students who have demonstrated exemplary academic and personal achievements, as well as interest and potential in metallurgy or materials science and engineering. Three awards of $2000 each are funded by the ASM Materials Education Foundation.



Skyler Burke

Iowa State University

Burke is entering his sophomore year, studying materials science and engineering at Iowa State University. His passion for materials science began in high school, when his materials science teacher did a lab with Nitinol. Burke attended the Eisenman Materials Camp for students in 2018. After his freshman year at Iowa State, he interned for Olsson Associates as a materials testing intern, working with various materials in the construction field.

Rachel Eckert

Iowa State University

Eckert has been captivated by materials science since she first heard about it. Taking STEM classes, job shadowing engineers, and attending ASM Materials Camps in high school confirmed that it was the career for her. Eckert is a junior materials engineering major at Iowa State, specializing in polymers and minoring in biomedical engineering. She has contributed to research at the Department of Energy's Ames Laboratory, served as Material Advantage secretary, and led the PrISUm solar car team as vice president.

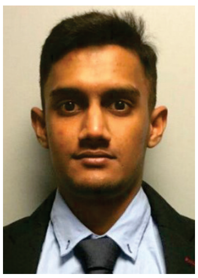
Mark Petrovic

Drexel University

Petrovic is in his last year in Drexel University's BS/MS program in materials science and engineering. He was introduced to the field of biomedical materials after joining the Biomaterials Laboratory Group during his freshman year. His thesis project focuses on the relationship between the chemical composition of heart valve tissue and its mechanical properties, specifically as it pertains to the function of tissue-derived heart valve replacements called bioprosthetic heart valves.

Edward J. Dulis Scholarship

The Edward J. Dulis Scholarship was established in 2003 and is awarded to an outstanding undergraduate member of ASM at the junior or senior level who demonstrates exemplary academic and personal achievements, as well as interest and potential in metallurgy or materials science and engineering. One scholar will receive a certificate and check for $1500 toward educational expenses for one academic year.



Siddhant Iyer

University of Massachusetts

Iyer is a senior in the plastics engineering department at UMass Lowell. He is co-founder and chief technology officer of EnVivoMed, as well as an undergraduate researcher at the Fabric Discovery Center affiliated with UMass Lowell under the mentorship of Dr. Ramaswamy Nagarajan. Iyer works on the interface of polymer science, optoelectronics, and wearables for applications entailing sustainable methods for energy generation and storage.

ASM MATERIALS EDUCATION FOUNDATION

2020 Undergraduate Design Competition Winners Announced

The ASM Materials Education Foundation and Design Competition Committee are pleased to announce the winners of the 2020 Undergraduate Design Competition. First prize goes to **Michigan Technological University** for "Increasing the Young's Modulus of Cast Aluminum for Automotive/Aerospace Applications." Team members include Wyatt Gratz, Joel Komurka, Ryan Lester, Zeke Marchel, and advisor Paul Sanders. The team will receive $2000, along with $500 to the department to support future design teams.

Second prize goes to **California State Polytechnic University, Pomona** for "Electrodeposition of Metallic Films on 3D Printed Polymer Foams." Team members include Rogine Gomez, Alessandro Pereyra, and faculty advisor Vilupanur A. Ravi, FASM. The team will receive $1500. Third prize goes to **Virginia Polytechnic Institute and State University** for "Increasing Conductivity of Polymers for Fiber-Based Neural Probe Applications." Team members include Alec Seastrom, Emily Pence, Garrison Ferrell, and Zach Krupa. The team will receive $1000.

Nomination Deadline for the 2021 Class of Fellows is Fast Approaching

The honor of Fellow of the Society was established to provide recognition to ASM members for distinguished contributions in the field of materials science and engineering, and to develop a broadly based forum for technical and professional leaders to serve as advisors to the Society.

Criteria for the Fellow award include:

- Outstanding accomplishments in materials science or engineering
- Broad and productive achievement in production, manufacturing, management, design, development, research, or education
- Five years of current, continuous ASM membership

Deadline for nominations for the class of 2021 is **November 30, 2020.** To nominate someone, visit the ASM website to request a unique nomination form link. Rules and past recipients are available at asminternational.org/membership/awards/asm-fellows or by contacting Christine Hoover, 440.671.3858 or christine.hoover@asminternational.org.

ASM Nominating Committee Nominations Due

ASM International is seeking members to serve on the 2021 ASM Nominating Committee. The committee will select a nominee for 2021-2022 vice president (who will serve as president in 2022-2023) and three nominees for trustee. Candidates for this committee can only be proposed by a Chapter through its executive committee, an ASM committee or council, or an affiliate society board. **Nominations are due December 15.** For more information, contact Leslie Taylor at 440.338.5472 or leslie.taylor@asminternational.org, or visit asminternational.org/about/governance/nominating-committee.

CAREERHUB
POWERED BY ASM INTERNATIONAL

VISIT THE CAREER HUB

Matching job seekers to employers just got easier with ASM International's new CareerHub. After logging on to the ASM website, job seekers can upload a resume and do searches on hiring companies for free. Advanced searching allows filtering based on various aspects of materials science, e.g., R&D, failure analysis, lab environment, and manufacturing. Employers and suppliers can easily post jobs and set up pre-screen criteria to gain access to highly qualified, professional job seekers around the globe. For more information, visit the CareerHub site. http://careercenter.asminternational.org/.

Collaborative Strategic Planning

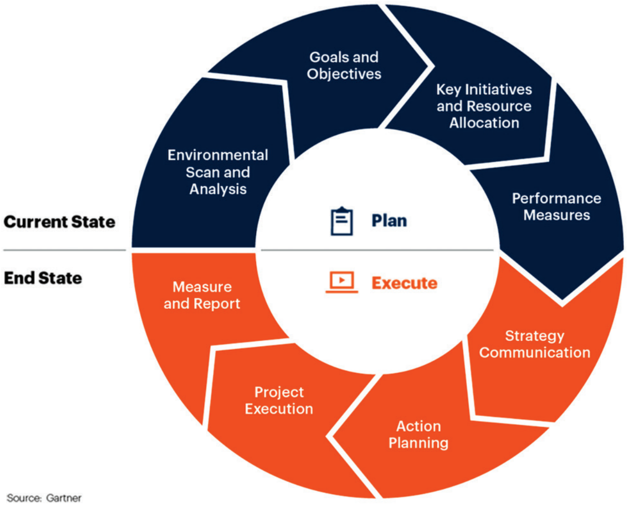
A Joint Message from ASM's President and Managing Director

Essock

Aderhold

Each year the ASM Board hones the Society's Strategic Plan. But this year, the ASM Strategic Plan was developed through a unique and collaborative process.

As part of the planning phase, the Board of Trustees and the Operations Team held working sessions in which they conducted an environmental scan and analysis, refined goals and objectives, identified key initiatives and resource allocations, and determined performance measures. The execution phase will be realized during the development of the annual operating plan, which will have several stage gate approvals: strategy communication, action planning, project execution, and measurement and reporting.



Strategic planning process 2020.

The strategic direction for the coming year is not a wholly new one, but updated based on the current environment including:

- Covid-19 Pandemic—employee safety, new ways of remote working
- Global Economic Conditions—when will the global economy restart
- Business and Industry Conditions—specifically for our members
- Implications from Virtual Meetings, Events (programming and Expo) and Networking
- Accelerated move to "Digital"
- Current Global Conversation on Diversity, Equity, and Inclusion (DEI)
- New Risks—what do we need to plan for
- Events and Education—how will these business lines change

Next, four strategic initiatives were identified as being key to ASM's future:

- Develop a Digital First Platform
- Establish an Interdisciplinary Collaboration Framework
- Create a Global Professional Network
- Cultivate a Culture and Practice of DEI

On July 7 and 8, ASM employees were invited to participate in any of four virtual brainstorming sessions to review the four strategic initiatives (digital, interdisciplinary, international partnerships, and diversity) and brainstorm ways to implement them. Board members attended as well. The sessions proved to be a creative way to build communication between members of the Board and ASM employees, but it also generated ideas that aided the Board's next phase of the process.

The Board of Trustees then met virtually for a full day Strategic Planning session on July 20. The mission and vision were reviewed, as well as the Board Task Forces. In the afternoon, brainstorming sessions were held in virtual breakout rooms on each of the four strategic initiatives (digital, interdisciplinary, international partnerships, and diversity) as well as a fifth session on technical networking. Each group examined their initiative with this question in mind: How do current and near-term environmental factors impact the strategic plan goals? As with the employee session, ideas were generated and documented, providing a wealth of opportunities to implement our strategic initiatives.

Developing and implementing a sound Strategic Plan is always our primary role as leaders of ASM International. This year, factoring in the changing environment was key. But also enhancing the communication and working relationship between the Board and Operations was one of the positive outcomes of our process. As another bonus, the challenges of meeting during this unusual time led to a unique method to involve a wider scope of participants. Contact either one of us to provide your input or ask questions. We look forward to working with you, the ASM membership, as we put the plans into place.

Diana Essock, FASM, ASM President, 2020-2021
diana.essock@asminternational.org

Ron Aderhold, Acting Managing Director, ASM International
ron.aderhold@asminternational.org

IMAT – The Virtual Edition

October 26-28

Mark your calendar now to be part of our first-ever ASM International virtual conference and expo, showcasing a select segment of technical programming, exhibits, and networking opportunities.

With the unfortunate cancellation of IMAT 2020 in Cleveland, the conference organizers wanted to provide an opportunity for the materials community to connect and engage via a virtual platform. **IMAT – The Virtual Edition** provides that opportunity and will also showcase a portion of the IMAT 2021 planned technical content and activities.

IMAT – The Virtual Edition will feature the following:

Technical Programming

Session organizers hand-selected more than 60 presentations to showcase during IMAT – The Virtual Edition. All sessions will be offered on-demand for up to 30 days following the event, so attendees will not have to choose between conflicting presentations.

Exhibit Hall

Visit the exhibit hall to view company profiles, live chat with exhibitors via instant messenger, and learn more about the latest products and solutions for the materials community.

Networking

Connect with colleagues, presenters, experts, and exhibitors via live chats and online messaging while receiving up-to-date information. In addition, meet and interact with other attendees during live networking events, including:

- IMAT Battle of the Brains—Trivia and Happy Hour
- Virtual Tour and Demos of the ASM International Labs
- Special Virtual Event at the Rock and Roll Hall of Fame: “Treasures from the Vault: Beatles Spotlight”

NASA Glenn Tour

Join NASA Glenn engineers for a virtual tour including the Simulated Lunar Operations Laboratory (SLOPE) and the Ballistic Impact Facility. You’ll want to arrive early because space is limited!

ASM is committed to supporting our members during these unprecedented times caused by the COVID-19 pandemic. With that in mind, IMAT – The Virtual Edition will be FREE for ASM members and students, and $75 for non-members.

FROM THE FOUNDATION

2020: A Year of Challenges and Opportunities


Wilson

The year 2020 has been full of challenges to meet and new opportunities to explore. The ASM Materials Education Foundation moved to online Materials Camps this summer for both students and teachers. Taking hands-on activities to an online platform required some imagination, but the alternative of not serving students and teachers was unacceptable.

Participants appreciated the online programs—and they asked for more. Both students and teachers enjoyed the connectivity and camaraderie available in the programs. We have answered the requests and are expanding to provide new fall programming.

Teachers may attend free weekly webinars on a variety of topics, from Materials Camp curriculum and tips for online teaching to new subjects from an ASM International professional. And just as important, sharing and discussion is part of the weekly sessions as well as the ASM Connect online communities for teachers. Curriculum and other resources are also available there, with teachers encouraged to share their own versions of experiments and lessons that others might be able to use in their own classrooms.

Student camp participants are part of the ASM Connect community for Materials Camp alum so that they can continue to ask questions and receive information about the field, or anything they may want to ask their mentors.

Students appreciated the connections developed through online Materials Camps over the summer. In response, the ASM Foundation is offering a Materials Club for students to continue learning about materials science and connecting with other students with the same interest. This 10-week enrichment opportunity is offered for a fee and will include materials science concepts and experiments, along with the opportunity to work with ASM professionals and contact university materials science and engineering departments.

Additional opportunities are in the works for students and teachers to help with classroom activities, professional development, and additional enrichment. The ASM Foundation staff, volunteers, and master teachers are excited to share materials science resources through new 2020 channels that expand our reach. We will keep you posted as we take advantage of these new opportunities. And, as always, thank you for your continuing support!

Carrie Wilson
Executive Director
ASM Materials Education Foundation

HTS Heat Treating Society

HTS Award Deadlines

ASM HTS/Bodycote Best Paper in Heat Treating Contest

The ASM Heat Treating Society established the Best Paper in Heat Treating Award in 1997 to recognize a paper that represents advancement in heat treating technology, promotes heat treating in a substantial way, or represents a clear advancement in managing the business of heat treating.

The award, endowed by **Bodycote Thermal Process-North America,** is open to all students, in full time or part time education, at universities (or their equivalent) or colleges. Students who have graduated within the past three years and whose paper describes work completed while an undergraduate or post graduate student are also eligible. The winner will receive a plaque and a check for $2500. **Paper submission deadline is March 1, 2021.**

George H. Bodeen Heat Treating Achievement Award

ASM's Heat Treating Society (HTS) is currently seeking nominations for the George H. Bodeen Heat Treating Achievement Award, which recognizes distinguished and significant contributions to the field of heat treating through leadership, management, or engineering development of substantial commercial impact. **Recommendations must be submitted to ASM headquarters no later than February 1 of the year the award is to be presented.**

ASM HTS/Surface Combustion Emerging Leader Award

The ASM HTS/Surface Combustion Emerging Leader Award recognizes an outstanding early-to-midcareer heat treating professional whose accomplishments exhibit exceptional achievements in the heat treating industry. The award was created in recognition of Surface Combustion's 100-year anniversary in 2015. The winning young professional will best exemplify the ethics, education, ingenuity, and future leadership of our industry. **Recommendations must be submitted to ASM no later than February 1 of the year the award is to be presented.**

For nomination rules and forms for all three awards, visit the Heat Treating Society website at hts.asminternational.org and click on Membership & Networking and Society Awards. For additional information, or to submit a nomination, contact Mary Anne Jerson at 440.671.3877 or email maryanne.jerson@asminternational.org.

EDFAS Electronic Device Failure Analysis Society

Seeking Nominations for EDFAS Awards

The ASM Electronic Device Failure Analysis Society established two awards to recognize the accomplishments of its members. Nominate a worthy colleague today!

EDFAS Lifetime Achievement Award

The EDFAS Lifetime Achievement Award was established by the EDFAS Board of Directors in 2015 to recognize leaders in the EDFAS community who have devoted their time, knowledge, and abilities to the advancement of the electronic device failure analysis industry.

EDFAS President's Award

The EDFAS President's Award shall recognize exceptional service to EDFAS and the electronic device failure analysis community. Examples of such service include committee service, service on the board of directors, organization of conferences or symposia, development of education courses, and student and general public outreach. While any member of EDFAS is expected to further the Society's goals through service, this award shall recognize those who provide an exceptional amount of effort in their service to the Society.

Nomination deadline for both awards is March 1, 2021. For rules and nomination forms, visit the EDFAS website at edfas.org, click on Membership & Networking and then Society Awards, or contact Mary Anne Jerson at 440.671.3877 or maryanne.jerson@asminternational.org.

IMS International Metallographic Society
ASM INTERNATIONAL

IMS Salutes Corporate Sponsors

The International Metallographic Society (IMS) relies on corporate financial support to maintain its excellent awards program. IMS extends sincere appreciation to the following companies for their support.

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Emerging Professionals

EMERGING PROFESSIONALS

Graduate School to Industry: Transferable Skills

Brittnee Mound-Watson, EPC Co-chair

Recently on LinkedIn, I have had multiple graduate students reach out to me asking for advice on how to translate the skills developed in graduate school to an industry role. Here is a list of some of those skills that are transferable from academic life to working in industry:

- Identifying a problem and having the motivation to solve it: Motivation is a key word here. Hiring managers want to hear about how you were curious about the issue at hand and what tools you used to obtain the information to solve the problem. To prepare for an interview, list some problems you solved and bullet points on how you solved them. In an interview, you may be asked why your research is important to them. This is an opportunity to showcase your research on the company and highlight your problem-solving abilities.
- Organization: This is very simple, but I have learned that it is a skill that can set you apart from others on a team. As a graduate student, you have a lot going on: research, courses, conferences, professional society meetings, and football games. Discuss in an interview how you can manage multiple tasks at once and what you do to ensure each task is completed on time.
- Documentation of technical instructions: As an engineer or research scientist, you will need to write standard operating procedure manuals on how to perform a process. Being able to accurately document and capture important steps in a process are needed skills in industry. Not all graduate students had the opportunity to write such manuals, but all graduate students had to write a dissertation or thesis. Demonstrate that you can communicate scientific results and technical instructions to a wide audience with various backgrounds.

There are many more skills that could be listed. If you have anything else you would like to add, send Brittnee Mound-Watson a message through the Directory on ASM Connect!

If interested in the EPC or helping with future emerging professional programming or projects, contact Drew Fleming at drew.fleming@asminternational.org.

WOMEN IN ENGINEERING

This profile series introduces leading materials scientists from around the world who happen to be females. Here we speak with ***Patricia Silvana Carrizo,*** *chemical engineer, National Technological University Mendoza Regional Faculty, Mendoza Province, Argentina.*

Carrizo

What does your typical workday look like?

I teach in the department of chemical engineering at UTN FRM as Professor of Materials Science Practical Works, and I work as a researcher in the electromechanics department within the metallurgy laboratory year-round.

What part of your job do you like most?

I particularly enjoy working in the area of archaeometallurgy where I examine and investigate the past of historical metallic objects by studying how they were manufactured, and the processes and raw materials used. These analyses are also useful when teaching metallurgy and metallographic techniques to students. The artifacts have a story to tell, and if you know how to read and more importantly interpret, you can extract very important information. Our metallurgy laboratory is a resource for failure analysis tests in the western part of the country, and I serve as a failure analyst mainly for the oil industries that bring their case studies to us.

What is your greatest professional achievement?

So far my greatest professional achievement was being hired by the Municipality of Luján de Cuyo to give advice and take charge of the restoration and external inspection of work on the old iron bridge over the Mendoza River, built in 1890. I enjoyed the magnitude of the work, the experience, and even though I was in charge of around 25-30 men, they collaborated well and respected the protocols and the instructions that I gave them. To my surprise, the workers there told me, "Patricia, you are no longer a boss for us, we highly esteem you and you are already part of us!"

Favorite motto or quote:

"The eye never forgets what the heart has seen."
– African proverb

Are you actively engaged with ASM or its affiliates?

I have belonged to the ASM Failure Analysis Society on the International Relations Committee since 2019 and I've recently joined ASM's IDEA Committee.

Do you know someone who should be featured in an upcoming Women in Engineering profile? Contact Vicki Burt at vicki.burt@asminternational.org.

CHAPTERS IN THE NEWS

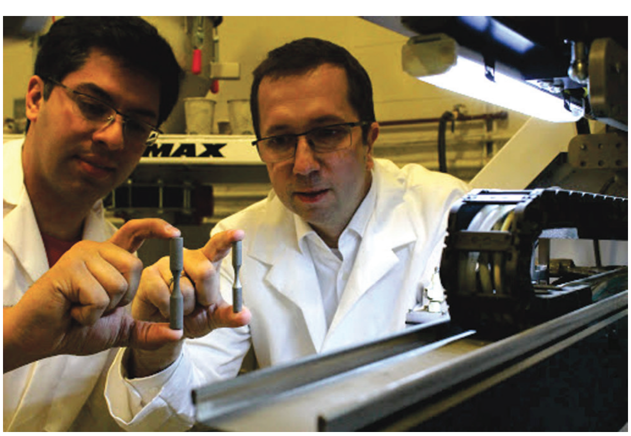
Leadership Days Goes Virtual

With COVID-19 cancelling in-person meetings, ASM Leadership Days successfully transitioned to a virtual training event. Chapter officers were able to attend webinar sessions on Chapter Finances, ASM Connect, Programming, and more! A Virtual Networking Mixer (truly BYOB) was even held to help officers connect with one another. Over 65 officers from various Chapters attended the virtual event with many sessions recorded and available for on-demand viewing.

ASM Chapter Council Chair JP Singh, FASM, opens the virtual 2020 Leadership Days session on September 15.

Pittsburgh Features COVID-19 Topics

The ASM Pittsburgh Chapter held its first virtual meeting on May 21 using the Ring Central/Zoom platform. Featured were two presentations related to the COVID-19 pandemic and the shortage of personal protection equipment (PPE). Dr. Markus Chmielus, an assistant professor in the Mechanical Engineering and Materials Science Department at the University of Pittsburgh presented “Promising Reusable Respirators with 3D Printed Metal Filters.” *AM&P* magazine will feature an article by Dr. Chmielus on a related topic slated for the February 2021 issue, as part of the Materials Science & Coronavirus series. The second topic of the evening, “PPE for COVID” was presented by two America Makes executives, John Wilczynsk, executive director and Alexander Steeb, operations director. They co-authored the article on page 22 of this issue that is also part of the Materials Science & Coronavirus series.



Dr. Markus Chmielus (right) in the AM^3 lab at the University of Pittsburgh.

100TH ANNIVERSARY

Congratulations to these ASM Chapters celebrating 100 years of serving local members!

Eastern New York
Hartford
Indianapolis

Thank you for your commitment!
We look forward to celebrating your future success!

MEMBERS IN THE NEWS

Liu Awarded Endowed Chair

Zi-Kui Liu, FASM, recently received the endowed chair in the Department of Materials Science and Engineering at The Pennsylvania State University. His title now reads, Dorothy Pate Enright Professor of Materials Science and Engineering. Prior to the new designation, Liu was distinguished professor of materials science and engineering at Penn State. Liu obtained his B.S. from Central South University (China), M.S. from University of Science and Technology, Beijing, and Ph.D. from KTH Royal Institute of Technology (Sweden). His research activities are centered on first-principle calculations, modeling of thermodynamic and kinetic properties, and their integration in understanding defects, phase stability, and phase transformations, and designing and tailoring materials processing and properties. He was the cofounder and director of the NSF Industry/University Cooperative Research Center for Computational Materials Design. Liu is currently the immediate past president of ASM International.

Liu

Folk Named VP at Ra Medical Systems

Chris Folk was appointed vice president of engineering at Ra Medical Systems Inc., Carlsbad, Calif., medical device company focusing on commercializing excimer laser systems to treat vascular and dermatological diseases. With more than 20 years of engineering experience primarily in medtech, Dr. Folk has led the design, development, and engineering of novel medical devices with highly specific design requirements, leading to commercial success. Prior to the appointment, he worked at Microfabrica Corp. and General Electric. Folk holds a B.S. in aerospace engineering from the University of Notre Dame, an M.S. in engineering mechanics from the University of Cincinnati and a Ph.D. in aerospace engineering from the University of California, Los Angeles.


Folk

Rivnay Recognized by MRS

Jonathan Rivnay, associate professor of biomedical engineering at Northwestern University, Evanston, Ill., was named a 2020 recipient of the Outstanding Early-Career Investigator Award by the Materials Research Society (MRS). He was cited "for innovative research on an organic semiconductor microstructure and charge transport for electronics and bioelectronics." The Outstanding Early-Career Investigator Award recognizes outstanding, interdisciplinary scientific work in materials research by a young scientist or engineer. The award recipient must show exceptional promise as a developing leader in the materials area.


Rivnay

IN MEMORIAM

Norman George Feige, Jr., FASM, a resident of Rockport, Ind., died on June 17 at age 88. Born in Evansville he was raised in Wauwatosa, Wisc. He graduated from the School of Engineering at the University of Wisconsin as a metallurgical engineer and earned credits toward a master's degree at Rensselaer Polytechnic Institute. He spent most of his professional career in the titanium industry, where he was responsible for the engineering and manufacturing of materials as well as several management positions. Feige published 33 papers about the metals industry and earned five patents. Later in his career, he established an independent consulting firm, which provided technical support in material applications and evaluation of material field failures. He was a member of several professional societies and in 1985 was made an ASM Fellow. For 32 years, he lived in South Salem, N.Y., and was member of the ASM Hudson Valley Chapter before retiring to Rockport. He also had been a member the ASM Western Kentucky Chapter.


Pearsall

George W. Pearsall died at age 82 on February 21, 2016. ASM was recently informed of his passing. Born on Long Island, N.Y., he served honorably in the U.S. Army during the Korean War. He earned a bachelor of metallurgical engineering degree from Rensselaer Polytechnic Institute and then joined Dow Chemical as a research engineer. In 1961, he received a doctor of science degree from the Massachusetts Institute of Technology (MIT), and served on the MIT faculty for four years before moving to Duke University. His research focused on material failure analysis and its relationship to product safety and design. During his over 30 years at Duke, Pearsall was dean of the MEMS department in the Pratt School of Engineering and was founding trustee of the Triangle Universities Center for Advanced Studies, Inc., which facilitated the location of the National Humanities Center, the Microelectronics Center of North Carolina, and the North Carolina Biotechnology Center in Research Triangle Park. He helped initiate Duke's Program in Science, Technology, and Human Values, and he was the first director of an experimental program at Duke in Technology and the Liberal Arts. He received the Triodyne Safety Award from the American Society of Mechanical Engineers in 2001 for his contributions to safe design practices. He was a member of the ASM Carolinas Central Chapter.

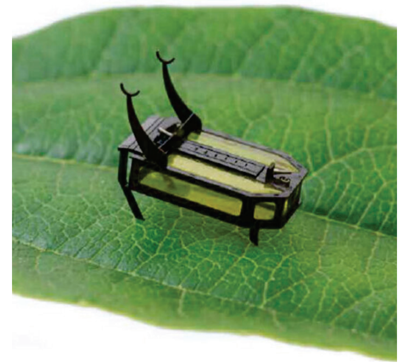
STRESS RELIEF

ROBOT BEETLE GOES THE DISTANCE SOLO THANKS TO A METHANOL-FUELED MICROMUSCLE

Scientists envision that swarms of robotic insects could assist search-and-rescue operations. Yet tight spaces are out of reach for robots that must be tethered to an energy source. Enter the new bot in town that carries its liquid fuel inside its body.

"I realized the critical issue was power," says Néstor O. Pérez-Arancibia. His team at the University of Southern California in Los Angeles turned to methanol because in a given mass, it packs over 10 times the energy as tiny batteries.

To turn methanol into motion, the researchers coated a nickel-titanium alloy wire with platinum. The alloy contracts like a muscle when heated, and extends when cool. The platinum generates heat by combusting any methanol vapor that comes in contact with it. By varying the exposure to fuel in a periodic pattern, the temperature varies and the micromuscle accordions. That motion causes the bot's forelegs to rear up. When the legs scooch back again, the body drags forward.



Look ma, no wires! A tiny robotic beetle crawls, carries, and climbs without being connected to a power source. Courtesy of X. Yang, et al./Sci. Robot.

Excluding fuel, the beetle bot weighs about as much as three grains of rice, on par with live insects. It crawls on flat surfaces while carrying up to 2.6 times its weight. It tackles inclines steeper than the toughest treadmill setting. And it can run for over one hour, Pérez-Arancibia says. With a battery—even a state-of-the-art one—it would run for a few seconds at best, he estimates.

There's room for improvement: The beetle is slower than comparable robots and can't be steered. Next-generation prototypes will use the same artificial muscle principle with a speedier, more maneuverable design and a different fuel.

Flying robots are his ultimate goal. Specifically? "We want to do butterflies," he says.

STATEMENT OF OWNERSHIP, MANAGEMENT, CIRCULATION, ETC.

Required by the Act of 23 October 1962, Section 4369, Title 39, United States Code, showing the ownership, management, and circulation of *Advanced Materials & Processes*®, publishes eight issues per year: January, February/March, April, May/June, July/August, September, October and November/December at 9639 Kinsman Road, Materials Park, Ohio 44073, USPS # 762-080. Annual subscription rate is $475.

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I certify that the statements made by me above are correct and complete.
Scott D. Henry, Publisher

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- FTIR Microscopy
- Monel: Part II

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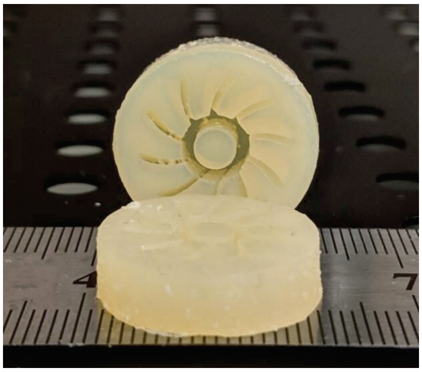
3D PRINTSHOP



This impeller was 3D printed with latex rubber at 100-micron resolution and exhibits a unique combination of flexibility and toughness. Courtesy of Virginia Tech.

3D PRINTED LATEX RUBBER BREAKTHROUGH

Virginia Tech researchers have discovered a novel process to 3D print latex rubber, unlocking the ability to print a variety of elastic materials with complex geometric shapes. The team chemically modified liquid latexes to make them printable and built a custom 3D printer with an embedded computer vision system to print accurate, high-resolution features of the high-performance material. 3D printed latex and elastomers could be used for a variety of applications including soft robotics, medical devices, or shock absorbers.

Commercial liquid latex is extremely fragile and difficult to alter, so the chemists built a scaffold around the latex particles to hold them in place. This way the latex could maintain its structure while photoinitiators and other compounds were added to enable 3D printing using vat photopolymerization, which uses ultraviolet (UV) light to cure the material into a specific shape.

The team also developed a printer capable of printing high-resolution features across a large area. Even with the custom printer, the fluid latex particles caused scattering outside of the projected UV light on the latex resin surface, which resulted in printing inaccurate parts. The researchers embedded a camera onto the printer to capture an image of each vat of latex resin. With a custom algorithm, the machine is able to "see" the UV light's interaction on the resin surface and then automatically adjust the printing parameters to correct for the resin scattering to cure just the intended shape.

The final 3D printed latex parts exhibited strong mechanical properties in a matrix known as a semi-interpenetrating polymer network, which had not been documented for elastomeric latexes in the prior literature. *vt.edu.*

LASER INVERSION ENABLES MULTI-MATERIALS 3D PRINTING

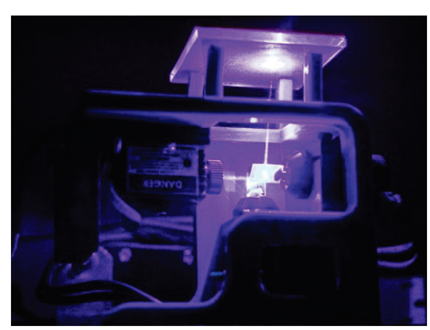
Researchers at Columbia Engineering, New York City, developed a new approach to selective laser sintering (SLS) which allows creation of parts from multiple materials. Traditional SLS fuses together material particles using a laser pointing downward into a heated print bed. A solid object is built from the bottom up, with the printer placing down a uniform layer of powder and using the laser to selectively fuse some material in the layer. The printer then deposits a second layer of powder onto the first layer, the laser fuses new material to the material in the previous layer, and the process is repeated over and over until the part is completed.

This process works well if there is just one material used in the printing process. But using multiple materials in a single print has been very challenging, because after the powder layer is deposited onto the bed, it cannot be unplaced, or replaced with a different powder.

"Also," adds Ph.D. student John Whitehead, "in a standard printer, because each of the successive layers placed down are homogeneous, the unfused material obscures your view of the object being printed, until you remove the finished part at the end of the cycle. This means that a print failure won't necessarily be found until the print is completed, wasting time and money."

The researchers found a way to eliminate the need for a powder bed entirely. They set up multiple transparent glass plates, each coated with a thin layer of a different plastic powder, lowered a print platform onto the upper surface of one of the powders, and directed a laser beam up from below the plate and through the plate's bottom. This process selectively sinters some powder onto the print platform in a pre-programmed pattern according to a virtual blueprint. The platform is then raised with the fused material, and moved to another plate, coated with a different powder, where the process is repeated. This allows multiple materials to either be incorporated into a single layer or stacked. Meanwhile, the old, used-up plate is replenished.

Researchers are now experimenting with metallic powders and resins to directly generate parts with a wider range of mechanical, electrical, and chemical properties than is possible with conventional SLS systems today. *www.engineering.columbia.edu.*



Laser beam transmitting upward through glass. Courtesy of John Whitehead, Columbia Engineering.