Celebrating 100 years

AMERICAN CERAMIC SOCIETY

bulletin

emerging ceramics & glass technology

APRIL 2021

Additive manufacturing of ceramics with microflash sintering

New issue inside:

Thixotropic support bath for 3D printing | 3D metrology global markets | FIRST Robotics

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April 2021 • Vol. 100 No.3

feature articles

Correction to the March 2021 *ACerS Bulletin*

Names in the news, page 11– Affiliation for Michel Barsoum should read Distinguished Professor in the materials science and engineering department at Drexel University.

department

columns

meetings

resources

AMERICAN CERAMIC SOCIETY
bulletin

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As seen on *Ceramic Tech Today...*

Credit: HarvardX, YouTube

Exploring characteristics of bronze-casting molds

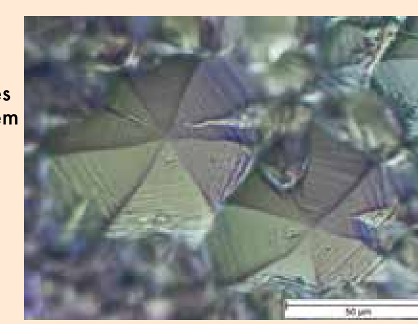
Ceramic molds used to cast bronze pieces during the Bronze Age offer one way to understand diachronic change and regional variation in metallurgical industries during that period. Researchers developed a novel FTIR-based approach for estimating the firing temperatures of these molds.

Read more at www.ceramics.org/bronzecasting

Also see our ACerS journals...

Materials research & measurement needs for ceramics additive manufacturing
By A. J. Allen, I. Levin, and S. E. Witt
Journal of the American Ceramic Society

Optimization and semi-automatic evaluation of a frosting process for a soda lime silicate glass based on phosphoric acid
By F. Kleiner
International Journal of Applied Glass Science



Porous structures printed by fused deposition of granules processed from a novel polyamide/alumina-based system
By Y. M. X Hung Hung, M. H. Talou, and M. A. Camerucci
International Journal of Applied Ceramic Technology

Processing and properties of SiC composites made via binder jet 3D printing and infiltration and pyrolysis of preceramic polymer
By C. L. Cramer, H. Armstrong, A. Flores-Betancourt, et al.
International Journal of Ceramic Engineering & Science

Read more at www.ceramics.org/journals

American Ceramic Society Bulletin covers news and activities of the Society and its members, includes items of interest to the ceramics community, and provides the most current information concerning all aspects of ceramic technology, including R&D, manufacturing, engineering, and marketing. The American Ceramic Society is not responsible for the accuracy of information in the editorial, articles, and advertising sections of this publication. Readers should independently evaluate the accuracy of any statement in the editorial, articles, and advertising sections of this publication. *American Ceramic Society Bulletin* (ISSN No. 0002-7812). ©2021. Printed in the United States of America. *ACerS Bulletin* is published monthly, except for February, July, and November, as a "dual-media" magazine in print and electronic formats (www.ceramics.org). Editorial and Subscription Offices: 550 Polaris Parkway, Suite 510, Westerville, OH 43082-7045. Subscription included with The American Ceramic Society membership. Nonmember print subscription rates, including online access: United States and Canada, 1 year $135; international, 1 year $150.* Rates include shipping charges. International Remail Service is standard outside of the United States and Canada. *International nonmembers also may elect to receive an electronic-only, email delivery subscription for $100. Single issues, January–October/November: member $6 per issue; nonmember $15 per issue. December issue (*ceramicSOURCE*): member $20, nonmember $40. Postage/handling for single issues: United States and Canada, $3 per item; United States and Canada Expedited (UPS 2nd day air), $8 per item; International Standard, $6 per item.

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ACSBA7, Vol. 100, No. 3, pp 1– 64. All feature articles are covered in Current Contents.

news & trends

Strategic charging infrastructure can lead to strong electric vehicle ecosystem

On Jan. 25, 2021, U.S. President Joe Biden signed the "Made in America" executive order to direct agencies to close current loopholes in how domestic content is measured and increase domestic content requirements, initiatives that ideally will spur investment in the nascent electric vehicle market.

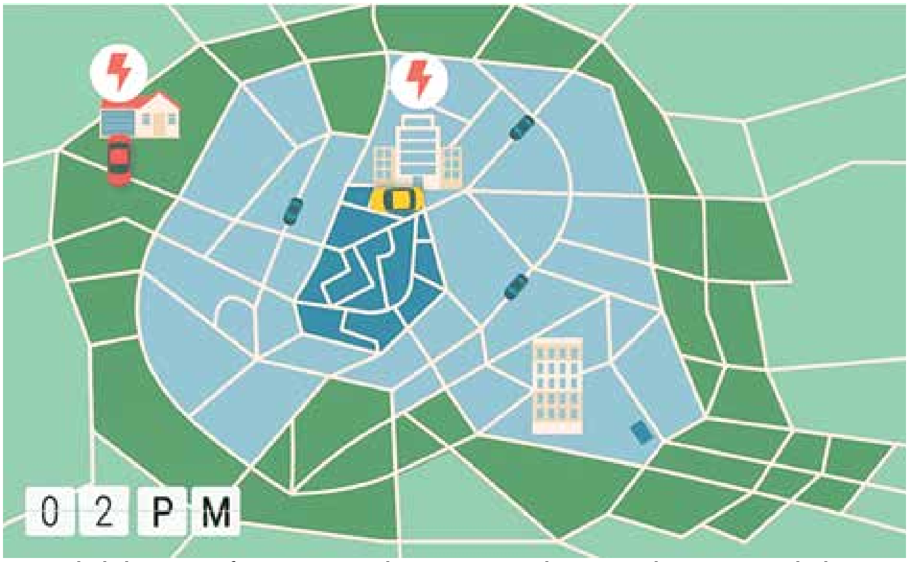
However, even if U.S. automakers conform to these standards and prepare to manufacture more electric vehicles, the U.S. sorely lacks the infrastructure necessary to support an electric vehicle ecosystem. Fortunately, numerous research groups are investigating solutions for improving the infrastructure, such as one group at the Massachusetts Institute of Technology.

The MIT researchers are led by associate professor of energy studies Jessika Trancik. They recently published a study that focuses on two potential solutions to support electrification: expanded charging infrastructure, and access to supplementary long-range vehicles (e.g., private or commercial car sharing, or an additional car at home).

"Expanded home, work and public charging infrastructure may address both real and imagined range constraints by allowing drivers to charge between and during trips," they write in the paper. "Accessing a supplementary vehicle with a longer range than the personally owned BEV [battery electric vehicle] could also address vehicle-days with high energy requirements and thus support BEV adoption."

Using driving habits in Seattle as the basis for their analysis, the researchers found that the number of homes that could meet their driving needs with a lower-cost electric vehicle increased from 10% to 40% when either highway fast-charging stations were added or availability of supplementary long-range vehicles was increased for up to four days a year.

This number rose to more than 90% of households when fast-charging stations, workplace charging, overnight



Credit: Trancik Lab, Massachusetts Institute of Technology

Expanded charging infrastructure and access to supplementary long-range vehicles are two important parts of developing a strong electric vehicle ecosystem.

public charging, and up to 10 days of access to supplementary vehicles were all available. Across all scenarios, charging options at residential locations (on or off-street) was key.

In the MIT press release, Trancik says there are various ways to incentivize expansion of such infrastructures. "There's a role for policymakers at the federal level, for example, for incentives to encourage private sector competition in this space, and demonstration sites for testing out, through public-private partnerships, the rapid expansion of the charging infrastructure," she says. State and local governments can also play an important part in driving innovation by businesses, she adds.

As policymakers make these decisions, though, Trancik says this study should help provide some guidance on where to focus building first. "If you have limited funds, which you typically always do, then it's just really important to prioritize," she says.

The paper, published in *Nature Energy*, is "Personal vehicle electrification and charging solutions for high-energy days" (DOI: 10.1038/s41560-020-00752-y).

International Year of Glass: Resolution for the General Assembly of the UN ongoing

The International Commission on Glass, the Community of Glass Associations, and ICOM-Glass are promoting a United Nations International Year of Glass for 2022. Its aim is to underline the scientific and economic importance of glass, the unseen heart of so many technologies and a facilitator of just and sustainable societies as they face the challenges of globalization.

A formal presentation was streamed worldwide via YouTube on Dec. 3, 2020. In February 2021, the Spanish mission in the United Nations, with the support of the Egyptian delegation, initiated the process of delivering the Resolution to the General Assembly. They received support from UNIDO, the United Nations body focused on industrial development, who are now editing a final draft of the Resolution.

Learn more about the initiative to declare 2022 the International Year of Glass, and register your interest at http://www.iyog2022.org.

Corporate Partner News

Fusion Ceramics Inc. celebrates 50 years in business

Fusion Ceramics was established in 1971 in Northeastern Ohio to manufacture glass frits for ceramic whitewares. Over time, custom glazes, engobes, and other ceramic blends were developed, as were new frits for the brick, refractories, and abrasives markets. Recent product line additions include glass colors, precious metal decorations, and water-based glass paints. Fusion supplies products throughout North America and has maintained a strong focus on customer service. As we celebrate 50 years of "Made in America" service and look to the future, Fusion would like to sincerely thank its customers and suppliers for their business and support.

Hyperloop—A possible future for transportation

The Hyperloop is a proposed mode of passenger and freight transportation that would use magnetic levitation and electromagnetic propulsion to send sleek metal pods hurtling through low-pressure, windowless vacuum tubes at hundreds of miles per hour.

The idea of using pneumatic tubes to travel is decades old, but the recent interest in "vacuum trains" started in 2013 when a joint team from Tesla and SpaceX published an early design for such a system. The name "Hyperloop" was chosen

A computer-generated image of the proposed Hyperloop, a potential new mode of passenger and freight transportation.

for their design because it would go in a loop. By November 2015, several commercial companies and dozens of student teams had started pursuing development of Hyperloop technologies.

Virgin Hyperloop (formerly Hyperloop One, and before that, Hyperloop Technologies) is one company pursuing commercial development of a Hyperloop system. It aims to achieve safety certification for its system by 2025, with commercial operations beginning in 2030. In November 2020, Virgin Hyperloop took a major step toward this goal by performing the first-ever Hyperloop passenger test at their 500-meter DevLoop test site in Las Vegas, Nevada. (The company has previously run more than 400 unoccupied tests on the site.)

There are several potential routes in the U.S. and around the world that the company is considering for its Hyperloop system, but one route being discussed for the Midwest would connect Chicago to Pittsburgh, with passage through Columbus, Ohio.

That possible Midwest route was considered by the Mid-Ohio Regional Planning Commission when it launched the Rapid Speed Transportation Initiative in 2018 to find better, faster connections between Columbus and the cities of Chicago and Pittsburgh. The results of the "Midwest Connect" Hyperloop Feasibility Study were released in May 2020, and the study concluded that Hyperloop technology is feasible along the Chicago–Columbus–Pittsburgh route at its optimal speeds of more than 500 mph.

Ohio, along with 16 other state and local governments, put in bids to host Virgin Hyperloop's planned testing and certification center. Virgin Hyperloop ultimately chose West Virginia in October 2020, but that does not mean Ohio will not play a larger role in developing a Midwest Hyperloop route in the future.

3D metrology: Global markets

By BCC Publishing Staff

The global market for 3D metrology was valued at more than $9.4 billion in 2019 and is forecast to reach almost $15 billion by 2025, growing at a compound annual growth rate (CAGR) of 13.8% during the forecast period.

3D metrology is the scientific study of physical measurement. However, in looser terms, it is often referred to as the field of precision measurement within industry. Applying 3D metrology means accurately obtaining an object's geometrical data in three axes (*x*, *y*, *z*). Metrology measurements are generally secured using a variety of techniques and hardware, including coordinate measuring machines, portable measuring arms, laser trackers, industrial 3D laser scanners, industrial theodolites, and light scanners.

Key drivers for the global 3D metrology market include

- **Demand of precision manufacturing:** Precision manufacturing allows manufacturers to produce parts with very tight tolerances in fields where even the slightest deviation is not an option, such as automotive, aerospace, electronics, and medical. 3D metrology helps precision manufacturers ensure parts and components fit and function as intended, despite the different languages, processes, and measurement systems used.
- **Stringent regulations for product safety and standardization:** Quality control programs are stringent across major industries. 3D metrology solutions such as coordinate measuring machines offer one of the most effective ways to create and manage meticulous quality control.
- **Automated optical inspection for growing PCB sector:** The printed circuit board industry is evolving and enhancing, with respect to product design and reliability and in response to more unified regulations and commercial standards. The 3D metrology method of automated optical inspection can detect missing components, uneven soldering, tombstones, and misaligned parts in the PCB assembly process.
- **Changing product lifecycles:** Products are shifting with respect to altering product development and life cycles, upcoming production technologies, and changing quality regulations and standards. 3D metrology assists in the production of quality products by implementing metrology solutions, such as providing fast measurements and results and clear visualization of measurement reports.
- **Industry 4.0:** The Fourth Industrial Revolution i.e., Industry 4.0, refers to the deployment of automation of traditional manufacturing by using smart technologies and intelligent systems. Portable 3D metrology equipment will support the rise of smart factories in various ways, including reverse engineering, prototype part inspection, low volume production measurements, tooling and fixture inspection and alignment, and the interrogation of product quality issues.

The key restraint for the global 3D metrology market will be selection of appropriate 3D metrology solutions. With the upcoming technologies and adoption of Industry 4.0, high precision metrology solutions should be sourced carefully to ensure that they represent the best fit for industrial applications.

Due to the strong presence of manufacturing brands targeted at industries such as automotive, aerospace and defense, and medical that uses 3D metrology on a large scale, North America's market for 3D metrology is slated to account for the largest share of global market revenues. The deployment of technologies geared for more productive and safer manufacturing processes will remain the key factor in this region's market-leading position.

Table 1. Global market for 3D metrology, by product type, through 2025 ($ millions)

Product	2019	2020	2022	2025	CAGR% (2020–2025)
Coordinate measuring machine	3,104.2	2,626.0	3,391.4	5,389.2	15.5%
Optical digitizer and scanner	2,351.7	1,933.6	2,359.2	3,443.1	12.2%
Video measuring machine	1,975.4	1,633.1	2,015.2	2,994.0	12.9%
Automated optical inspection	1,128.8	953.7	1,228.8	1,946.1	15.3%
Form measurement	846.6	692.4	835.6	1,197.6	11.6%
Total	9,406.6	7,838.8	9,830.0	14,970.0	13.8%

About the author

BCC Publishing Staff comprises expert analysts who are skilled in conducting primary research, secondary research, and data analysis and have decades of combined experience covering a wide range of industries. Contact the staff at info@bccresearch.com.

Resource

BCC Publishing Staff, "3D Metrology: Global Markets" BCC Research Report IAS169A, March 2021. www.bccresearch.com.

By Lisa McDonald

Into the Bulletin Archives—A look back at our 100 years in print

Since May 1922, the *ACerS Bulletin* has served the ACerS community, providing them updates on member news, Division meetings, and the latest research in ceramics and glass.

In celebration of Volume 100 this year, the *Bulletin* editorial team is running a special column in each issue of the 2021 *Bulletin* that looks at the history of the *Bulletin* by decade. This issue highlights the 1940s.

We hope you enjoy following the journey of the *Bulletin* from its early years to today. As an ACerS member, you have access to all 100 years of the *Bulletin* on the *Bulletin Archive Online* at https://bulletin-archive.ceramics.org.

Into the *Bulletin* Archives—1940s

The *Bulletins* of the late 1930s and early 1940s looked very similar on the surface—for the cover, they both regularly used headshots of people profiled later in the issue. However, in 1944 and 1945, the *Bulletin* covers featured the ACerS' logo instead, and starting in 1946, they began being printed in color for the first time.

During this decade, the world bore witness to the end of World War II in May 1945. Though the war itself is not explicitly debated within the *Bulletin*, articles discussing the effects of the war on ACerS members and the ceramic industry appear frequently in issues of this time.

For example,

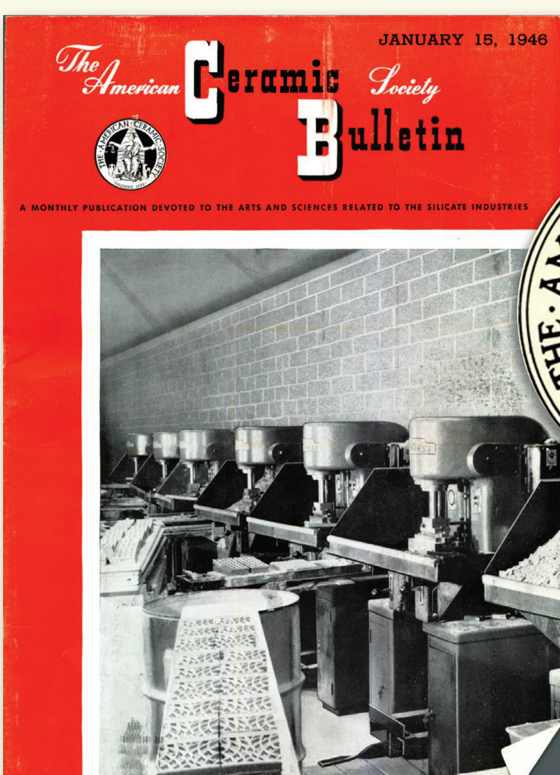
- February 1945: "The ceramic industry: Now and postwar" (pp. 46–55)
- August 1945: "War veterans in the postwar ceramic industry" (pp. 282–288)
- September 1945: "The ceramic industry and the returned serviceman" (pp. 320–322)

The desire for articles on these topics was evident in letters from servicemen published in the *Bulletin*, such as the one below.

"Dear Sirs:

I realize very much that I've fallen down in my duties to The Society, and about the only excuse I have is that the Army has kept me very busy in the past few months. ...

1940s



Credit: *ACerS Bulletin* (January 1946) Vol. 25 Iss. 1, front cover

Full color covers became a feature of the *Bulletin* starting in 1946. The first image framed in bright, bold red was of Denison HydrOILic Multipresses forming ceramic radiants for gas heaters.

Credit: *ACerS Bulletin* (January 1944) Vol. 23 Iss. 1, front cover

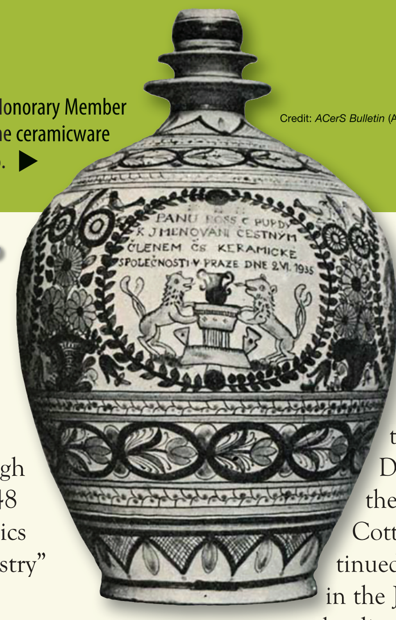
▲ This early logo of The American Ceramic Society was used as the cover for *Bulletin* issues in 1944 and 1945.

DIVISIONS OF THE SOCIETY

During the 1940s, the Society had seven Divisions.

- Design (previously Art)
- Enamel
- Glass
- Materials and Equipment
- Refractories
- Structural Clay Products
- White Wares
- ~~Terra Cotta~~ (Discontinued in 1940)

Vase presented to Ross Purdy in June 1935 upon his election as Honorary Member of the Czechoslovak Ceramic Society. This vase was included in the ceramicware collection that Purdy gifted to ACerS upon his retirement in 1946. ▶



Credit: *ACerS Bulletin* (April 1946) Vol. 25 Iss. 4, pp. 166

What I am interested in is some information and advice from The Society. I received my degree in ceramic engineering at Georgia Tech in February, 1943, and went immediately into the Army. I feel that after the war I would like to take a short refresher course before entering the field. My big question is—has The American Ceramic Society any setup for aiding returning servicemen in finding positions in the ceramic field? I would certainly appreciate any help and information you could give me on this matter."

–*ACerS Bulletin, Vol. 24., Iss. 5., May 1945*

In addition to the effects on industry, the role ceramic materials played in science relevant to the war was covered. In particular, ceramics used in nuclear physics, a nascent and contentious research field at the time, received thorough coverage in a July 1948 article, "Nuclear physics and the ceramic industry" (pp. 263–267).

For the Society, the year following the end of WWII proved notable when Ross Coffin Purdy retired in April 1946 from active service as General Secretary and Editor, a dual position which he had served in for 24 years. Upon retirement, Purdy willed to ACerS his extensive library of books and pamphlets, his gallery and albums of photographs, and his collection of ceramicware. Purdy passed away only three years later on January 6, and his obituary appears in the January 1949 *Bulletin*.

The Society witnessed two major changes to its Divisions structure during the 1940s. One, the Terra Cotta Division was discontinued in 1940. A statement in the June 1940 issue explains the dissolution was due mainly to "economic conditions prevailing in the terra cotta manufacturing industry in the United States during the past few years [that] have caused a lack of interest on the part of manufacturers and their technically trained employees in support of the Terra Cotta Division." Two, the *Bulletin* reported that the Art Division was renamed the Design Division as of January 1943; no explanation for this change is given.

SOCIETY DIVISION SECTION CHAPTER NEWS

Welcome new ACerS Corporate Partners

ACerS is pleased to welcome its newest Corporate Partner:

– **Monofrax**

To learn about the benefits of ACerS corporate partnership, contact Kevin Thompson, membership director, at (614) 794-5894 or kthompson@ceramics.org.

Volunteer spotlight

ACerS Volunteer Spotlight profiles a member who demonstrates outstanding service to the Society.

Ericks

Andrew Ericks received his B.S. in metallurgical and materials engineering from the Colorado School of Mines in 2018, and he is currently a third-year Ph.D. candidate in the Materials Department at the University of California, Santa Barbara.

Ericks has volunteered with ACerS since 2018. As a President's Council of Student Advisors (PCSA) delegate on the Outreach Committee and as Outreach chair, he has contributed to several endeavors, including PCSA's Day in the Life videos, outreach to delegates' local communities, and development of the Materials Science Classroom Kits. Currently, he is in his second year as a delegate to the Engineering Ceramics Division. Ericks also serves as a peer reviewer for the *Journal of the American Ceramic Society*.

We extend our deep appreciation to Ericks for his service to our Society!

Germany Chapter co-hosts "3rd International Sustainability Workshop focused on Gender Equality"

The Germany Chapter and the Materials Research Society International Chapter at the University of Cologne co-hosted the "3rd International Sustainability Workshop focused on Gender Equality" on March 5. During this free event, women from different scientific disciplines shared their experiences and gave an insight into women in science.

For more information, go to https://sustainability.uni-koeln.de.

Newly formed Japan Chapter hosts inaugural event

The International Symposium at the Ceramics Society of Japan Annual Spring Meeting (virtual) will be co-organized with the Ceramic Society of Japan and the new Japan Chapter of ACerS. Program details can be found at https://bit.ly/38qXFZ8. For more information, visit the meeting page at https://sites.google.com/ceramic.or.jp/nenkai2021.

Colorado Section introduces mentor program

The Colorado Section is introducing a mentoring program is looking for mentees and mentors. Mentees who are looking to build skills, boost their resume, and network with professionals should apply at https://bit.ly/3sfrnaI. Mentors with successful materials science careers and who would like to give back can apply at https://bit.ly/3qQZW78.

Names in the news

Members—Would you like to be included in the Bulletin's Names in the News? Please send a current head shot along with the link to the article to mmartin@ceramics.org. The deadline is the 30th of each month.

Laurencin

Cato T. Laurencin was named the 2021 Kappa Delta Ann Doner Vaughn Award recipient for his 30 years of scientific breakthroughs in musculoskeletal regenerative engineering, the field which he founded and brought to the forefront of translational medicine.

Central Ohio Section launches book club

The Central Ohio Section is launching a virtual book club. The Section's selection will be communicated, and the book club will wrap up with a Zoom fireside chat (date TBD). The hour-long virtual meeting will be an open format to allow lively conversation about the book. Congratulations to Central Ohio for providing a safe, socially distanced networking event.

Cements Division's 11th Advances in Cement-Based Materials Virtual Meeting

Cement is the key ingredient in concrete—the most-used building material in the world—so every advance in understanding how it behaves presents an opportunity to reduce greenhouse gases, advance construction engineering, and improve quality of life around the globe. Organized by the Cements Division, the 11th Advances in Cement-Based Materials will take place as a virtual meeting June 23–25, 2021. Additional information may be found at http://bit.ly/cements2021.

IN MEMORIAM

Peter Fleischner

Jon Hines

Charles Sorrell

Some detailed obituaries can also be found on the ACerS website, www.ceramics.org/in-memoriam.

Frontiers of Ceramics & Glass Webinar Series

APRIL 15
2:00 PM EST

Title: *To come*

PRESENTER:
SUROJIT GUPTA – University of North Dakota
ACerS Engineering Ceramics Division

Free to ACerS members

The ACerS Frontiers of Ceramics and Glass Webinar Series offers free, live webinars for members each month providing valuable technical content in a convenient format. Expert speakers from ACerS Divisions, Sections, and Chapters deliver knowledge on a variety of cutting-edge topics while answering questions live from viewers.

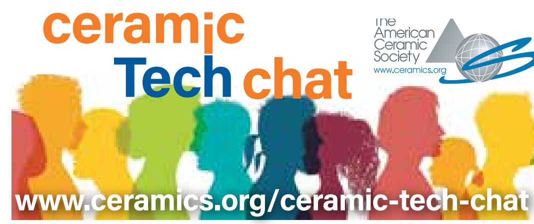
Presented by the ECD, Surojit Gupta will use case studies to explore ideation and opportunity analysis for designing high performance materials.

There is no cost for ACerS members, GGRN, or Material Advantage student members, and members can access previous webinar recordings. The registration fee for nonmembers is $30 and $15 for student nonmembers.

For more information and registration, visit http://bit.ly/ACerSWebSeries.

more SOCIETY DIVISION SECTION CHAPTER NEWS

Ceramic Tech Chat: Taylor Sparks and Andrew Falkowski



Hosted by ACerS Bulletin editors, Ceramic Tech Chat talks with ACerS members to learn about their unique and personal stories of how they found their way to careers in ceramics. New episodes publish the second Wednesday of each month.

In the February episode of Ceramic Tech Chat, Taylor Sparks and Andrew Falkowski, associate professor and BS/MS student, respectively, at the University of Utah, discuss how they got into the field of materials science, what led them to start their podcast Materialism, and offer ways for scientists to improve their science communication skills.

Check out a preview from their episode, which features Sparks explaining why they use a narrative style for communicating scientific concepts.

> *We did an episode on artificial dialysis, so artificial organs. And when you tell the background that this was happening in Nazi Germany, while it was the Nazis that invaded the Netherlands. And this guy was not a Nazi sympathizer, he was not a fan of them. And yet his first patient that he installed this artificial kidney on was a woman who was a Nazi sympathizer and how conflicted he must have been. And you talk about the tools he used was an old washing machine and orange juice cans and it was like sausage casing. That was the first artificial, or dialysis organ. So your mind engages with that information in a totally different way. And so it's been really fun to structure our episodes wherever possible around that narrative."*

Listen to Sparks and Falkowski's interview—and all of our other Ceramic Tech Chat episodes—at http://ceramictechchat.ceramics.org/974767. 100

AWARDS AND DEADLINES

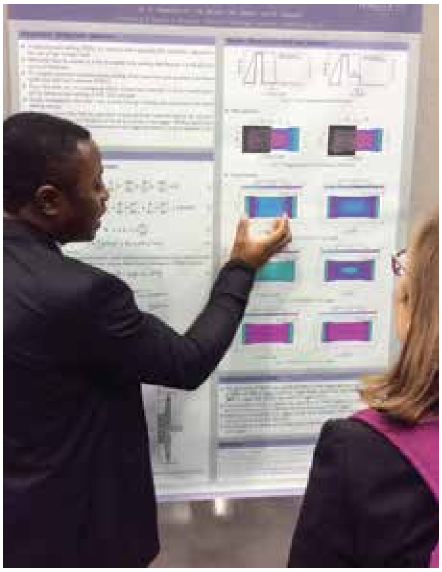
Division	Award	Nomination Deadline
GOMD	Alfred R. Cooper Scholars	May 15
Electronics	Edward C. Henry	May 15
Electronics	Lewis C. Hoffman Scholarship	May 15
Engineering Ceramics	James I. Mueller	July 1
Engineering Ceramics	Bridge Building	July 1
Engineering Ceramics	Global Young Investigator	July 1
Engineering Ceramics	Jubilee Global Diversity	July 1

FOR MORE INFORMATION:

ceramics.org/members/awards

Contacts	Description
Steve Martin swmartin@iastate.edu	Recognizes undergraduate students who have demonstrated excellence in research, engineering, and/or study in glass science or technology.
Matjaz Spretizer matjaz.spreitzer@ijs.si	Recognizes an outstanding paper reporting original work in the *Journal of the American Ceramic Society* or *ACerS Bulletin* during the previous calendar year on a subject related to electronic ceramics.
Matjaz Spretizer matjaz.spreitzer@ijs.si	Recognizes academic interest and excellence among undergraduate students in ceramics/materials science and engineering.
Valerie Wiesner valerie.l.wiesner@nasa.gov	Recognizes the accomplishments of individuals who have made important contributions to the ECD and field of engineering ceramics.
Hisayuki Suematsu suematsu@vos.nagaokaut.ac.jp	Recognizes individuals outside of the United States who have made outstanding contributions to engineering ceramics.
Palani Balaya mpepb@nus.edu.sg	Recognizes an outstanding scientist who is conducting research in academia, industry, or at a government-funded laboratory.
Michael Halbig michael.c.halbig@nasa.gov	Recognizes exceptional early- to mid-career women and/or underrepresented minorities (i.e., based on race, ethnicity, nationality, and/or geographic location) in the area of ceramic science and engineering.

STUDENTS AND OUTREACH



Your dream job is out there—the Career Center helps you find it

Online recruitment continues to gain support from organizations looking for top talent. Over the last two years, companies have spent thousands of dollars raising brand awareness on the Ceramic and Glass Career Center to attract more interested job seekers—like you—to fill their open positions. See, for example, the testimonial from Corning on p. 15. Visit the online Ceramic and Glass Career Center at https://careers.ceramics.org to look at current openings, access a myriad of career resources, and post your resume for employers to find you.

The Pennsylvania State University–American Ceramic Society–University of Kiel (PACK) International Research Experience Fellowship

PACK is a National Science Foundation funded international research fellowship opportunity for graduate students (U.S. citizens or permanent residents only) to conduct research at University of Kiel, Germany. Plans are now underway to resume travel for PACK Fellows to study at University of Kiel, with the target date of Nov. 1, 2021. Applications are accepted year-round, so it is never too early to apply for the next cohort. Find out more and apply for the PACK International Fellowship at http://packfellowship.org.

ACerS GGRN for young ceramic and glass researchers

Put yourself on the path toward post-graduate success with ACerS Global Graduate Researcher Network. ACerS GGRN is a network that addresses the professional and career development needs of graduate-level research students who have a primary interest in ceramics and glass.

GGRN aims to help graduate students

- Engage with ACerS,
- Build a network of peers and contacts within the ceramic and glass community, and
- Gain access to professional development tools.

Are you a current graduate student who could benefit from additional networking within the ceramic and glass community? Visit www.ceramics.org/ggrn to learn what GGRN can do for you, or contact Yolanda Natividad, membership engagement manager, at ynatividad@ceramics.org.

Did you graduate recently? ACerS has a gift for you!

ACerS Associate Membership connects you to the field's top technical content, meetings, and minds. ACerS can help you succeed by offering you the gift of a FREE Associate Membership for the first year following graduation. Your second year of membership is only $40. Associate members have access to leadership development programs, special networking receptions, volunteer opportunities, and more.

Let ACerS make your transition to a seasoned professional easier. Start your free year-long membership by visiting www.ceramics.org/associate or contact Yolanda Natividad, member engagement manager, at ynatividad@ceramics.org.

FOR MORE INFORMATION:

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CERAMIC AND GLASS INDUSTRY FOUNDATION

Valuable member benefit: Ceramic and Glass Career Center postings

The search for a qualified ceramic and glass professional to fill open positions should be neither time consuming nor expensive. Fortunately, ACerS Corporate Partners have the valuable member benefit of posting jobs for free on the CGIF's online Ceramic and Glass Career Center.

Dozens of companies in the ceramic and glass community have saved precious time and money by posting their open positions on our site, where qualified professionals go to find their next great opportunity.

Using the Ceramic and Glass Career Center, employers can search our resume database of qualified candidates, find those applicants that fit the employer's requirements, and fill open positions more quickly with great talent.

According to Peter Diamantakos, staffing consultant for the Science & Technology Group at Corning, Inc., "I have found posting my jobs on the Ceramic and Glass Career Center and searching the database to be very helpful in finding ideal candidates."

Once an employer creates a free account on the Ceramic and Career Center site, it is easy to select the type of job posting desired and submit the information in the job listing. Jobs and applicant activity can be managed directly on our site.

As an added benefit of membership, ACerS Corporate Partners can receive a coupon code that allows them to post a 30-day job listing for free. A coupon also is available to receive 30% off the Ultimate Recruitment Package. Nonprofit organizations, educational institutions, and government entities associated with ACerS also are eligible for discount coupons.

If you want to quickly connect with highly engaged professionals through same-day job postings, please visit the Ceramic and Glass Career Center at https://careers.ceramics.org. Contact Belinda Raines, CGIF program manager, at braines@ceramics.org to receive a coupon code for free or discounted job postings.

Glass discovery and design: 21 challenges in artificial intelligence and machine learning for glass science

Glass has played an extensive role in the lives of humans for over two millennia, from established applications such as kitchenware and windows to emerging applications such as bioactive implants and energy materials. However, despite the well-established history of this material, very few glasses among the total possible glass compositions have been discovered, and even fewer have been well-studied.

The traditional trial-and-error methodology for discovering glasses is the main reason for the limited knowledge on glass compositions. It is highly time-consuming, inefficient, and can be risky for industrial applications (for example, it may not produce the desired result).

Fortunately, recent advances in computer hardware and algorithms have led to the use of artificial intelligence (AI) and machine learning (ML) to aid in glass discovery and design. Artificial intelligence is a branch of computer science dealing with simulation of intelligent behavior in computers. Machine learning, a subset of AI, focuses on developing algorithms that can detect and understand patterns in data and extrapolate to previously unexplored domains and circumstances.

Credit: Pixabay

A recent paper published in *IJAGS* identifies 21 challenges that, when addressed, can aid in harnessing the full potential of these methods for glass science.

AI and ML approaches to materials design work well for glasses for several reasons, including the fact that the properties of glasses are mainly driven by composition due to their disordered structure. Thus, by applying AI/ML methods to large experimental databases of glass properties, researchers can in theory predict desirable new glass compositions quite easily.

Numerous research groups have developed models based on AI and ML to predict various properties of glass, including Young's modulus, solubility, and glass-transition temperature, among others. However, while these studies represent great strides in using AI and ML for glass science, challenges still exist to harnessing the full potential of these methods for discovering and designing new glasses—challenges that are outlined in a new paper published in *International Journal of Applied Glass Science*.

The researchers who wrote the recent paper are led by N. M. Anoop Krishnan, assistant professor in civil engineering and materials science and engineering at the Indian Institute of Technology Delhi (IIT-D). In an email, Krishnan says they aimed to take a step back and look at the field of glass science and technology in a holistic manner to identify the major challenges and solutions that are enabling or are enabled by AI and ML.

Krishnan says while the challenges they identified are not an exhaustive list, they "hope that the broad areas identified will instill enthusiasm to initiate a coordinated effort from the glass community to solve some of these challenges and also identify new challenges, ultimately accelerating the field of glass science."

The challenges identified in the paper broadly belong to two categories:

1. Challenges that can be addressed using AI and ML techniques.
2. Challenges that enable application of AI and ML techniques for accelerated glass design, discovery, and manufacturing.

Research News

Researchers develop improved recycling process for carbon fibers

Researchers from the University of Sydney's School of Civil Engineering developed an optimized method for recycling carbon fiber reinforced polymer (CFRP) composites while maintaining 90% of their original strength. CFRP composites are present in products such as wind turbines, airplane parts, and vehicles. They typically are disposed of in landfills or by incineration because most existing recycling methods cause a major reduction in the mechanical and physical properties of the recovered material. To combat this issue, the researchers used a two phased, optimized process involving pyrolysis and oxidation. For more information, visit https://www.sydney.edu.au/news-opinion/news/2021.html.

Sixth mirror cast for Giant Magellan Telescope

The University of Texas at Austin and other partners of the Giant Magellan Telescope announced the fabrication of the sixth of seven of the world's largest monolithic mirrors. These mirrors will allow astronomers to see farther into the universe with more detail than any other optical telescope before. The sixth 8.4-meter (27.5 feet) mirror is being fabricated at the University of Arizona's Richard F. Caris Mirror Lab and will take nearly four years to complete. The sixth mirror joins three others in various stages of production at the mirror lab; the first two giant mirrors are completed and in storage in Tucson. For more information, visit https://mcdonaldobservatory.org/news.

Challenges 1–4: Developing high-quality datasets

The predictions made by AI and ML models are only as good as the data on which the predictions are based. Thus, the authors begin their list by suggesting several ways to develop high-quality datasets, including

- Automating extraction of datasets from the literature,
- Improving detection of outliers in the data, and
- Developing consistent synthetic datasets, i.e., data generated from atomistic and first-principle simulations.

Challenges 5–12: Preparing and understanding algorithms

Having developed a high-quality dataset, the next group of challenges pertain to the algorithms used to analyze that data. The authors discuss numerous aspects that researchers should be aware of when designing algorithms, including

- Selecting the right input feature,
- Selecting relevant training algorithms, and
- Selecting appropriate hyperparameters.

The authors also emphasize the importance of infusing "common-sense" into the model by accounting for basic physical laws and to quantify uncertainty of the predictions. In addition, current ML methods are "notoriously known as black-box methods" due to the difficulty of interpreting the nature of the input–output relationships, so shedding more light on this process would be extremely beneficial.

Challenges 13–17: Disseminating knowledge in the field of glass science

To date, the AI/ML models for investigating composition–property relationships typically use simple composition-based descriptors because additional information that plays a crucial role in governing the properties—such as glass preparation protocols, testing methods, and environmental conditions—often are ignored or reported in a form that cannot be easily extracted from the text. The authors offer a few ways to address these challenges to knowledge dissemination, including

- Considering how to apply knowledge learned in one area to another area;
- Identifying appropriate keywords to facilitate discovery of the study;
- Briefly summarizing a study in a holistic manner, including images, text, and chemical species present;
- Reporting on and extracting synthesis parameters of the glasses in the dataset; and
- Creating a curated image library for the glasses from literature.

Challenges 18–21: Automating the process

The authors end their list by identifying several ways to streamline glass discovery and design by automating various steps of the process, including

- Automating the glass synthesis process,
- Automating scheduling of tasks,
- Automating detection of flaws during synthesis, and
- Automating warning and safety systems for glass industries.

Krishnan says his group is already working on addressing some of these challenges. For example, they developed a software package called Python for Glass Genomics that addresses at least three of the challenges:

1. Glass database from literature (PyGGi Bank).
2. Machine learned composition–property models (PyGGi Seer).
3. Optimized design of glasses (PyGGi Zen).

"We have also started efforts toward the application of natural language process (NLP) to address some of the challenges, such as: (i) automated extraction of glass data, (ii) information extraction from scientific literature and images, and (iii) development of image repository. A preprint from our group which addresses some of these challenges can be found at https://arxiv.org/abs/2101.01508," he says.

The paper, published in *International Journal of Applied Glass Science*, is "Artificial intelligence and machine learning in glass science and technology: 21 challenges for the 21st century" (DOI: 10.1111/ijag.15881).

Bioactive glass toothpaste is coming to America

U.K.-based company BioMin recently received FDA premarket clearance for its bioactive glass-containing toothpaste, opening the door for this product to finally be offered on the U.S. market.

Bioactive glass toothpastes have been available in other countries for at least a decade. Bioactive glass is a beneficial additive in toothpaste because, after brushing with toothpaste that contains this material, the bioactive glass reacts with saliva in the mouth and forms a protective mineral layer on the surface of the teeth. This layer is reported to help strengthen the enamel (although not necessarily repair any damage), protect against acid erosion, and, perhaps most notably, effectively treat tooth sensitivity.

Despite these known benefits, regulatory approval has hampered the availability of bioactive glass toothpaste in the U.S. market. Why? The story stretches back to 2009, when pharmaceutical giant GlaxoSmithKline (GSK) acquired bioactive glass startup NovaMin for some $135 million. In the years following, GSK proceeded to offer its Sensodyne Repair and Protect toothpaste product in markets beyond the U.S. with NovaMin bioactive glass included, yet puzzlingly omitted the bioactive glass from such products sold in the U.S.

There have been a lot of speculations and even conspiracy theories as to the omission, but it seems to come down to a lack of U.S. FDA clearance and the company deciding against investing to further pursue that clearance. Other countries outside the U.S. categorize toothpastes as a different type of product (cosmetics rather than drugs), so less prohibitive regulatory processes allowed bioactive glass to be more easily incorporated into toothpaste products abroad.

BioMin: Bringing bioactive glass back

In 2016, BioMin released its bioactive glass toothpaste in the U.K., with hopes to eventually gain FDA approval and expand to toothbrushes across the U.S.

Now, nearly five years later, that is finally happening. BioMin will offer its Restore Plus toothpaste under the Dr.Collins brand as the "first fluoride-containing bioactive glass toothpaste to be approved by the FDA for sale in the United States," according to a BioMin press release. The toothpaste will be available with a prescription in the U.S. starting spring 2021.

BioMin Restore Plus contains just 5% of its BioMin F bioactive glass formulation, but that small amount of bioactive material confers a disproportionately large benefit with its ability to form a long-lasting, acid-resistant, protective barrier on the tooth's surface. BioMin F is not the same as NovaMin bioactive glass, however, as BioMin F contains fluoride as well.

This point is an important one because it means brushing with BioMin F results in release of fluoride, calcium, and phosphate ions to form a protective layer of fluorapatite on the tooth's surface, in contrast to the hydroxyapatite layer that forms from calcium and phosphate ions with NovaMin.

"Fluorapatite is about a unit of pH more stable than hydroxyapatite. So hydroxyapatite will start to dissolve at about pH 5, whereas fluorapatite will start to dissolve at about pH 4. So once you form fluorapatite, it's less likely to be dissolved away. And that gives us an advantage," says Robert Hill, materials engineer and chief scientific officer for BioMin, in a video conference call.

While many other kinds of toothpastes contain fluoride in a soluble form, BioMin F is different in that it incorporates the fluoride into the glass structure. This strategy allows fluoride ions, as well as calcium and phosphate ions, to slowly dissolve from the bioactive glass over time, achieving a sustained release effect after brushing—at neutral pH, up to 8–12 hours.

This unique feature offered a unique challenge in terms of designing the bioactive glass because simply mixing the ions together would result in formation

Credit: BioMin

BioMin Restore Plus toothpaste, set to be available in the U.S. this spring, contains bioactive glass.

of fluorapatite in the toothpaste rather than on the tooth's surface. So BioMin designed the fluoride into the glass amorphous matrix so that it can be slowly released as the bioactive glass dissolves.

The resulting fluoride-containing bioactive glass that BioMin developed, called BioMin F, has higher phosphate content—about three times as much—as NovaMin, along with a lower silica content and smaller particle sizes.

The smaller size of BioMin's particles means the toothpaste itself is less abrasive. "The problems we have today with everybody using abrasive whitening toothpaste is the high abrasion causes a lot of damage to the tooth surface," says Colin Suzman, a dentist and owner of Dr.Collins, in the call. "But BioMin has a low relative dentin abrasion value, below the level that would cause abrasion of the tooth surface. So it's not only a chemical advantage but a mechanical advantage as well."

FDA clearance

BioMin received 510K premarket clearance from the FDA, a certification that clears the way for a product to be offered on the market. An accepted 510K demonstrates that a product is similar to an existing product on the market, so this clearance process can bypass the lengthy and expensive clinical trials that would be required to bring a completely new product to market.

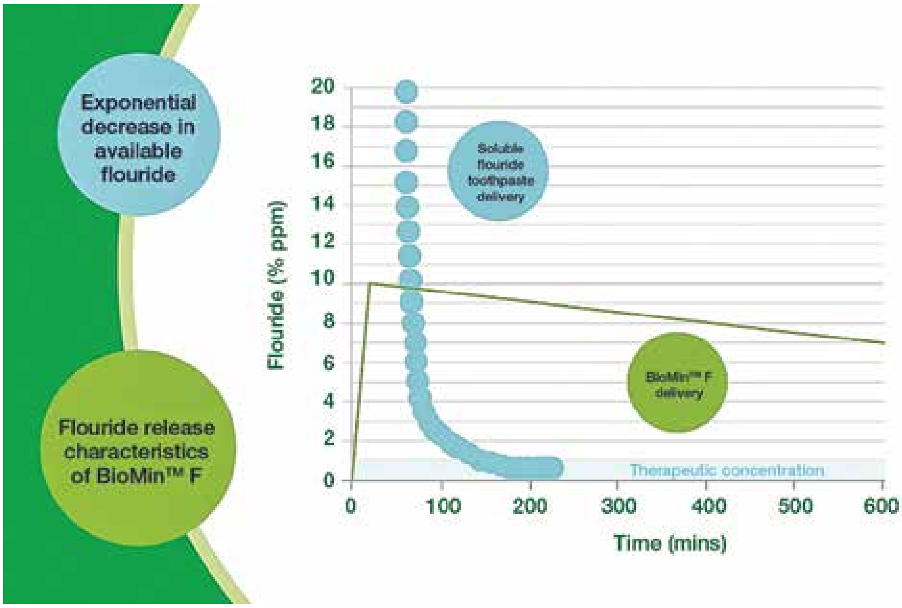
"I think the biggest hurdle was, generally speaking, we didn't really have a solid predicate device that was actually on the market," says Suzman, who was closely involved with the BioMin Restore Plus FDA clearance process. "So finding the right device and using that sort of as a bridge between our product and the discontinued NovaMin product was probably a challenge. There was a lot of back and forth with the FDA."

FDA clearance is a big deal for other products as well, whether from BioMin/Dr.Collins or their competitors. Now that one product is on the market, it could provide an established precedent that makes it much easier for similar types of products to come to market. Having a similar product on the market, what the FDA calls "substantial equivalence," was one of the main hurdles that BioMin Restore Plus faced. But with that hurdle now cleared, future 510K applications for similar types of products may be easier to get accepted.

Expanding horizons

BioMin is currently working on developing self-healing tooth fillings containing bioactive glass. Hill explains, "Rather than using inert glass in a resin matrix, we use some of the slightly different fluoride glasses from the ones used in the toothpaste. These ones we're designing so that if you've got any decay left by the dentist, providing it's not decay of the protein component, you can actually put back the mineral into the decay and dentine. And it will also deposit mineral in any gaps caused by polymerization shrinkage."

In addition to this research, "I think bioactive glasses have got a huge potential in oral care. We're looking at the next, say, 20 years," Whatley says. "We obviously believe this and hope this, but I think bioactive glasses have a huge opportunity to change and to improve the quality of materials used in dentistry." 100



Credit: BioMin

BioMin F bioactive glass incorporates fluoride into the glass structure to achieve slow release over time, whereas toothpastes that incorporate soluble fluoride generate high initial fluoride levels that decrease quickly after brushing.

ceramics in manufacturing

High-quality graphene from ultrafast, low-cost plasma spray

Bottles containing exfoliated graphene obtained from a new method based on plasma spraying. Reprinted with permission from Islam et al., *ACS Nano*, Vol. 15 Iss. 1 (1775–1784). Copyright 2021 American Chemical Society.

A recent study by four researchers from the Indian Institute of Technology Patna proposes a new high-temperature exfoliation method for graphene that may offer the best outcome for speed, cost, and material quality.

There are four essential factors of an ideal graphene production method: 1) it produces high-quality graphene, 2) it distributes graphene in narrow layers, 3) it uses a fast and reproducible technique, and 4) it allows for high throughput. Unfortunately, current methods of graphene production struggle to fulfill all four factors.

Bottom-up approaches such as chemical vapor deposition and epitaxial growth are the leading methods for graphene production. They offer the ability to grow high-quality graphene in a large area, but they currently lack bulk production protocols and remain expensive due to multistep processes.

Top-down approaches that involve exfoliating graphite to obtain graphene are scalable thanks to cheap and abundant graphite sources. But quality and narrow layer distribution of the graphene typically suffer, for example, in electrochemical exfoliation and mechanical exfoliation, respectively.

Researchers have conducted some studies on synthesizing graphene by exposing graphene precursors to high temperatures, but this approach tends to suffer from some of the same problems as other exfoliation methods, namely producing graphene with topological defects or multilayers.

The new method proposed in the recent study is based on plasma spraying, a well-established technique for depositing metal or ceramic coatings. In this process, powders of the coating materials are fed via an inert gas stream into a plasma jet, which melts the coating materials and then sprays them over the substrate to be coated.

In their study, the researchers used argon gas to introduce graphite directly into a plasma plume at a powder feed rate of 120 g/h. Then, they collected the plasma exposed graphite and introduced it to mild centrifugation in deionized water to remove unexfoliated large agglomerates.

The researchers used various microscopy and spectroscopy methods to analyze the exfoliated graphene, and the results were promising. The graphene flakes were up to 3 μm in diameter, with 85% being a single atomic layer and the rest having a few layers. The material was free of defects and had a high carbon-to-oxygen ratio of 21, which is comparable to graphene made using the bottom-down approach of chemical vapor deposition.

In a C&EN article, senior author Anup Kumar Keshri, assistant professor and head of the Department of Metallurgical and Materials Engineering at the Indian Institute of Technology Patna, says the technique yielded 48 grams of graphene in 1 hour, which suggests it should be easy to scale up.

In addition, because the method does not require any solvents, intercalants, or purification steps, cost of the lab-made graphene is only $1.12 per gram, which "is competitive or even lower than commercially available graphene" and should go down further when mass-produced.

"We believe that this work could be a game changer in the production of pristine graphene in large scale for numerous applications," the researchers conclude their paper.

The paper, published in *ACS Nano*, is "Ultra-fast, chemical-free, mass production of high quality exfoliated graphene" (DOI: 10.1021/acsnano.0c09451).

Bettering tungsten supply: Effects of grinding media on scheelite flotation

Researchers from Wuhan University of Science and Technology (China) investigated the effects that grinding media has on the flotation behavior of scheelite.

Scheelite ($CaWO_4$), along with wolframite ((Fe, Mn)WO_4), are the two main minerals that are mined commercially as a source of tungsten. Wolframite traditionally is the primary ore of tungsten, but in recent years the world has witnessed an increasing depletion of easily beneficiated wolframite resources. This depletion has led the industry to devote considerable interest to scheelite resources instead.

To obtain tungsten from scheelite, one of the main beneficiation methods used is flotation. Flotation involves altering an ore's surfaces to be either hydrophobic or hydrophilic, i.e., either repel or attract water. When the ore is placed in aerated water, the bubbles attract and then float the hydrophobic minerals, leaving the hydrophilic component in the underflow as tailings.

Much research on improving the flotation of scheelite looks at adjusting the flotation reagents, or the substances used to alter hydrophobicity and hydrophilicity. However, researchers often overlook another important factor that could potentially affect the scheelite flotation performance—grinding media.

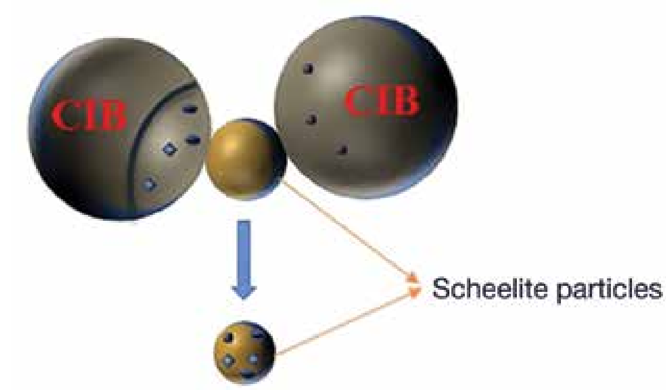
Before beginning the flotation process, the ore is scrubbed to condition its surface for further beneficiation. Cast iron balls are a first-choice media for grinding scheelite because of their cheap price and high grinding efficiency, but they can result in the ore having iron contamination.

Previous studies on materials such as sulfide minerals, platinum group metal, and carbonate minerals showed iron contamination has deleterious effects on flotation. "However, the effects of CIB [cast iron ball] grinding on the flotation behavior of scheelite are still unclear," the researchers write in their open-access paper.

They decided to fill this gap in knowledge by studying the effects of contamination themselves. They collected scheelite samples from Jiangxi Province, China, and then ground the scheelite using either cast iron balls or ceramic balls. (Previous studies showed using inert grinding media such as ceramic balls can enhance the sulfide flotation performance.)

They used a variety of tests to determine the effects of grinding material on the flotation process, including zeta potential measurements, dissolved oxygen tests, inductively coupled plasma-atomic emission spectroscopy tests, scanning electron microscopy-energy dispersive spectroscopy tests, and X-ray photoelectron spectroscopy tests.

Ultimately, the researchers concluded that scheelite ground by cast iron balls has a lower flotation recovery than scheelite ground by ceramic balls. They attribute this finding to the coating of iron species on the scheelite surface, which impedes adsorption of sodium oleate, a reagent that creates a hydrophobic film on the mineral surface.



Researchers in China investigated how grinding scheelite with cast iron balls can affect the flotation process by contaminating the mineral with iron.

"This research will guide the grinding medium selection in beneficiation of scheelite ore in industry and effectively improve the scheelite flotation performance, which is significant in the efficient use of tungsten resources," they write.

The open-access paper, published in *ACS Omega*, is "Effects and mechanisms of grinding media on the flotation behavior of scheelite" (DOI: 10.1021/acsomega.0c05104). 100

ceramics in energy

Putting the sun in a bottle: The path to delivering sustainable fusion power

The benefits, challenges, and progress in nuclear fusion power generation was the focus of this year's Kavli Medal and Lecture, which is awarded annually by The Royal Society to researchers who demonstrate excellence in all fields of science and engineering relevant to the environment. UK Atomic Energy Authority CEO Ian Chapman was this year's recipient "for his scientific insight that has illuminated the complex physics of confined plasmas and prepared the way for fusion burn," according to The Royal Society website.

Fusion is the reaction that powers the sun. It involves the creation of a new element by "smashing" together two atoms of other elements. The most common is the reaction of two forms of hydrogen atoms—deuterium and radioactive tritium—to form helium.

Fusion reactions release massive amounts of energy, so much so that the energy from fuel with the mass of a grain of sand could power a car for 20 minutes. If we could "put the sun in a bottle," i.e., control fusion reactions in a contained environment, it would offer a carbon-free power source with a high energy density, low waste, plenty of fuel (water and lithium), and the ability to run constantly (unlike wind and solar). Additionally, fusion reactors are considered to be inherently safe. Unlike nuclear fission, which gets energy from the splitting of heavy atoms, fusion does not have the potential for runaway reactions because fuel is fed slowly and interruptions will cause the reaction to stop.

The fusing of atoms requires input of extreme amounts of energy to overcome coulombic repulsion of atoms. In the sun, gravitational attraction provides the energy. In fusion reactors, the elemental reactants are accelerated into the reaction zone. The resulting reaction plasma is both very hot (millions of degrees) and unstable. Because the plasma cannot be contained by solid walls, it is isolated from the walls and stabilized by either electromagnetic fields or inertial fields.


Credit: Pixabay

The latest Kavli Lecture hosted by The Royal Society looks at the possible role of fusion energy in our sustainable energy future.

Inertial isolation is achieved by using high power lasers. Facilities such as the National Ignition Facility at Lawrence Livermore National Labs have delved quite deeply into high energy science, with many substantial advancements. But so far, "ignition" has not been achieved using laser confinement. (Ignition is when the plasma reaches net positive energy, i.e., more energy comes out of the reaction than is put into it.)

With electromagnetic containment, charged ions in motion are "steered" by magnetic forces. While a number of different electromagnetic configurations are being explored, the most mature technology uses tokamaks, which are toroidal (donut shaped) reactor designs first developed in Russia in the 1950s. As is true of the inertial isolation systems, electromagnetic containment systems have yet to achieve net positive energy.

There are several electromagnetically contained fusion demonstration systems around the world, include JET in the U.K., which achieves 16 megawatts of thermal energy output. Unfortunately, it uses 25 megawatts of energy.

The ITER project is being built in France through a global public-private partnership including governments, technology company charitable foundations, and energy companies. The project goal is to demonstrate net positive energy generation with a 500 megawatts reactor, including a 10x return on the 50 megawatts needed to accelerate the fuel. The project is about 75% complete, with a projected online date of 2025. However, it has already yielded benefits by creating new supply chain companies and factories to produce parts for ITER and, ideally, for construction of commercial fusion power plants.

In his lecture, Chapman says that the ITER design has some challenges. Most significantly, it is too large and thus too costly. He described ongoing work at the UK Atomic Energy Authority, including more efficient heat exhaust (MAST Upgrade) and a spherical tokamak (STEP). Chapman describes a spherical tokomak as an "apple with the core removed." The advantage of the spherical tokamak is the more efficient use of magnetic fields, resulting in smaller reactors and less expensive magnets.

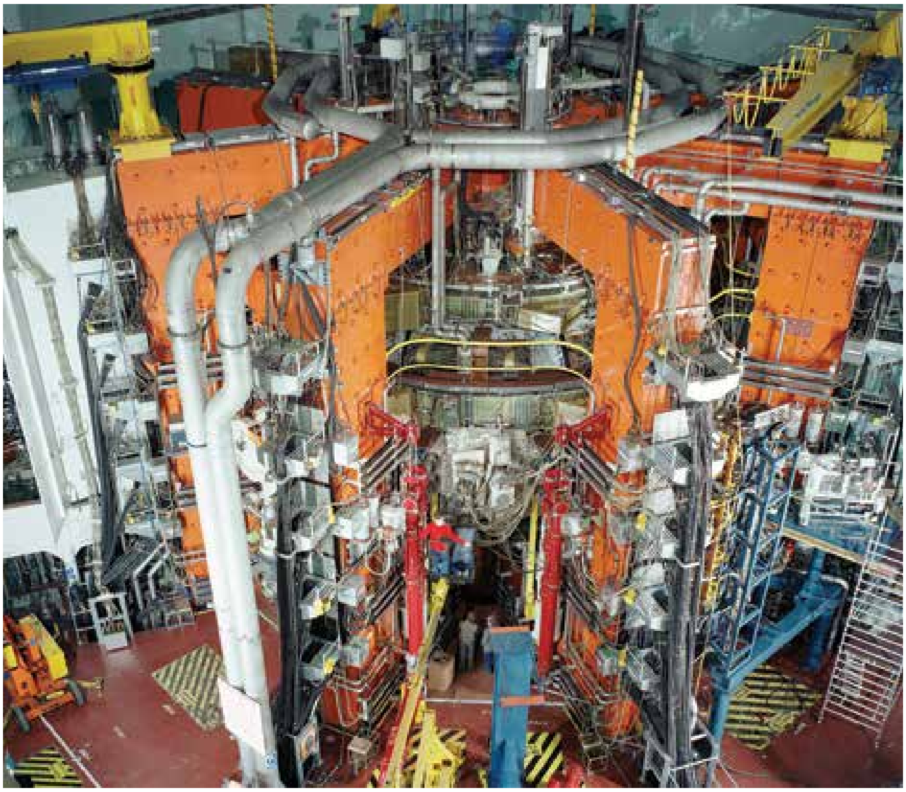
Materials challenges

Several materials challenges must be met for the technology to become cost effective and commercially viable. First, fusion releases extremely high energy neutrons that bombard the walls of the reactor. This bombardment results in rearrangement of the atomic structure that embrittles and weakens the walls. The most viable solution is to use sacrificial linings on the reactor walls that can last for a few months or years before needing to be replaced. This solution presents an opportunity for the development of ceramics that are resistant to tritium absorption along with the radiation bombardment. Silicon carbide is a promising material, as are MAX phase materials.

Additional research is being conducted on "aneutronic" fusion reaction systems that use fuels other than tritium and deuterium and do not release the neutron. There is much interest in using these reactors for space flight propulsion.

The second materials challenge comes from heat removal and substantial thermal gradients within and around the reactor. The reaction zone is 150 million degrees (10 times hotter than the sun), and the walls (about 2 meters away) are a few hundred to perhaps a few thousand degrees. Just behind the wall must be close to absolute zero (–270°C) for the magnet wires to become superconducting.

The third materials challenge is development of viable high-temperature superconductors. High temperatures in this case are still quite cold at around 77 Kelvin (–196°C). But liquid nitrogen is substantially less expensive than liquid helium, and the reduced temperature gradient provides more leeway for reactor wall development.



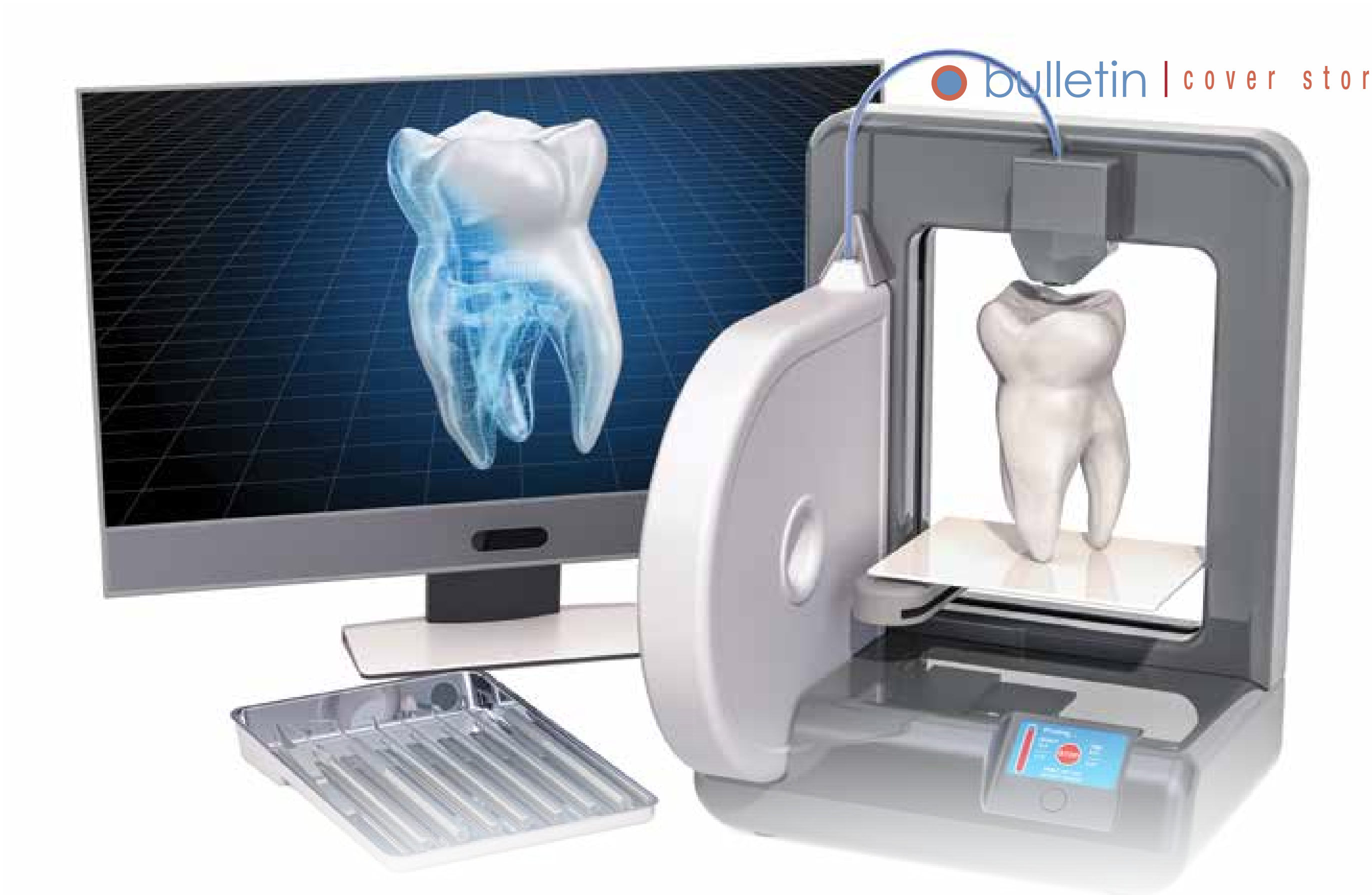
Credit: EFDA JET, Wikimedia (CC BY-SA 3.0)

Image of the JET fusion reactor from 1991.

Many technological challenges remain as well, such as development of in-situ robots to replace the reactor linings and perform other repairs in radioactive environments. Also, the efficiency of magnetic field generation must improve in order to reduce the size and cost of the reactors and power plants. The work of Chapman and others in the U.K. show promise in these areas and others.

Despite these challenges, the field of fusion energy generation will soon see major advances with the ITER project and the lessons that are being and will be learned from it. The materials and technological challenges provide opportunities for ceramic scientists and engineers now and for many years to come.

Watch the full 2019 Kavli Medal and Lecture athttps://www.youtube.com/watch?v=eYbNSgUQhdY. 100



Additive manufacturing of ceramics with microflash sintering

By Rubens Ingraci Neto and Rishi Raj

Combining two emerging processing technologies—microflash sintering and additive manufacturing—may enable fast production of high-density, arbitrarily shaped ceramic parts.

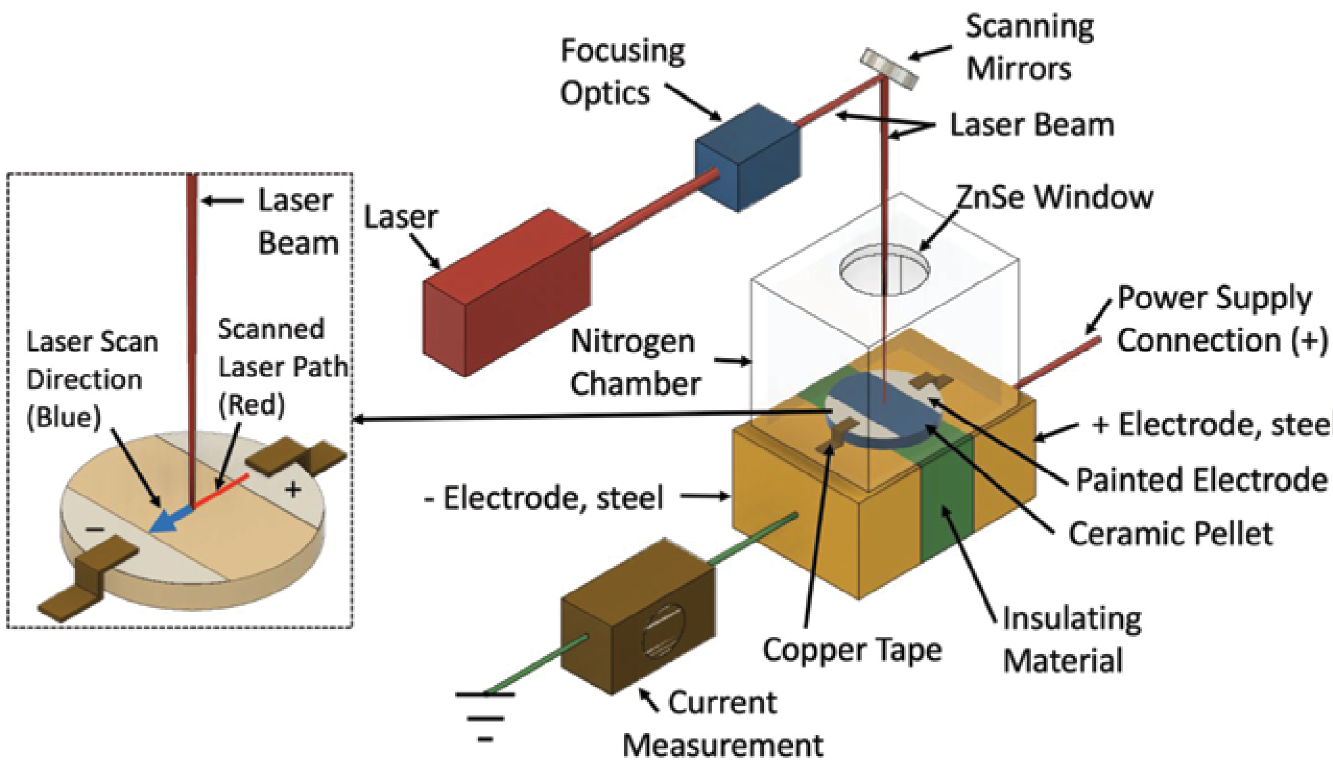
Additive manufacturing of advanced ceramics has the potential to reach a market of $4.8 billion by 2030.[1] So far, additive manufacturing of ceramics has focused on niche segments such as medical applications, but there is potential for application in mass markets.

To date, the additive manufacturing methods used for advanced ceramics include stereolithography, selective laser sintering, slurry-based 3D printing, laminated object manufacturing, and direct inkjet printing.[2] However, fabricating a three-dimensional ceramic body of an arbitrary shape with high density through additive manufacturing remains a challenge.[2]

Usually, a green body is prepared by stereolithography with photopolymerization of the binder. Large parts can be difficult to produce because of the tendency to deform and crack during binder pyrolysis. The green body then is sintered by conventional techniques.[3–5]

In selective laser flash sintering, poor resistance to thermal shock is an obstacle[2,6] because this method creates severe temperature gradients. Higher power densities, i.e., those greater than 100 W mm^{-3}, applied over a period of milliseconds to seconds are used.[7] The outcomes remain challenging. For instance, yttria-zirconia powder could be sintered only up to 56% of its theoretical density[8] and Al_2O_3 up to 33%.[9] This method often requires further sintering in a furnace to achieve high densities.

It is possible that additive manufacturing with microflash sintering (AM-MFS) can lead to fast production of high-density



Credit: Hagen et al., J Am Ceram Soc.

Figure 1. Schematic of selective laser flash sintering system from Hagen et al.[22]

parts of arbitrary shapes. Flash sintering, first discovered in 2010,[10] is achieved at low furnace temperatures in very short times. The technique is demonstrated to be viable in myriad materials, including high-temperature ceramics (SiC,[11,12] BC_4,[13] HfB_2[14]), solid oxide fuel cells (Co_2MnO_4,[15] $La_{0.8}Sr_{0.2}Ga_{0.8}Mg_{0.2}O_{3-\delta}$[16]), solid electrolytes for batteries ($Li_7La_3Zr_{1.9}Ta_{0.1}O_{12}$,[17] $Li_{0.5}La_{0.5}TiO_3$[18]), and structural ceramics (ZrO_2 and Al_2O_3)[19].

Flash sintering offers good control of process parameters because the degree of densification and the grain size are controlled by the current and the electrical field at low power.[20] It has been shown to be benign in situations of constrained sintering that can cause defects in conventional sintering. In this way the sintered spots grow on the workpiece to create a component that is ready for the end user.

Initial experiments on AM-MFS

The potential of an electric field coupled with additive manufacturing was first investigated by Hagen et al. (2019).[21] The authors integrated a power supply to an additive manufacturing system from nScrypt, which consisted of a slurry microdispenser and a yttrium aluminum garnet (YAG) laser. A slurry with 63 vol.% of ethanol, 25 vol.% of 8 mol% yttria-stabilized zirconia (8YSZ), and 12 vol.% of other additives was deposited on a metallic surface connected to the ground of the power supply. Then, the laser heated the deposited layers while a noncontact electrode floating over the slurry sustained an electric field of 1,000 V cm^{-1}. Unfortunately, no enhancement in sintering was observed because of binder decomposition when heated with the laser.

Later, this same research group developed a new laser assisted method in which small regions on the surface of an 8YSZ green pellet were sintered with a laser while an electric field was sustained by electrodes in contact with that surface (Fig. 1).[22] This custom-built selective laser flash sintering system reduced the necessary laser power to achieve densification.

Electric current flowing between the electrodes was recorded with fast laser scans (spanning less than 150 ms) at low power (9.3 W). However, the results were not reproducible. A patent describing the selective laser flash sintering method was filed in 2017.[23] It discusses possible configurations for a system that integrates flash sintering with additive manufacturing.

Continuous sintering via floating electrodes

In 2018, Sortino et al.[24] showed that a green ceramic strip could be sintered continuously by pulling it through a pair of line electrodes, pressing it gently against the surface, and aligning them normal to the pulling direction. The electrodes were made by bending a sheet of nickel superalloy to create an edge that made "sporadic" contact with the sliding work piece (Fig. 2).[24] The experiment succeeded. Key process variables were furnace temperature; field applied across the electrodes; current limit set at the power supply; and speed at which the strip, approximately 10 mm wide and 6 mm thick, was pulled through the electrodes.

The authors developed processing maps in the parameter space specified by the current density and pulling speed, and they identified three regimes. If the current was too low, then sintering was incomplete; if it was too high, it led to localization of current and poor microstructure. The safe regime lay at intermediate current densities and, rather surprisingly, at high speeds. In hindsight, they learned that uniform cur-

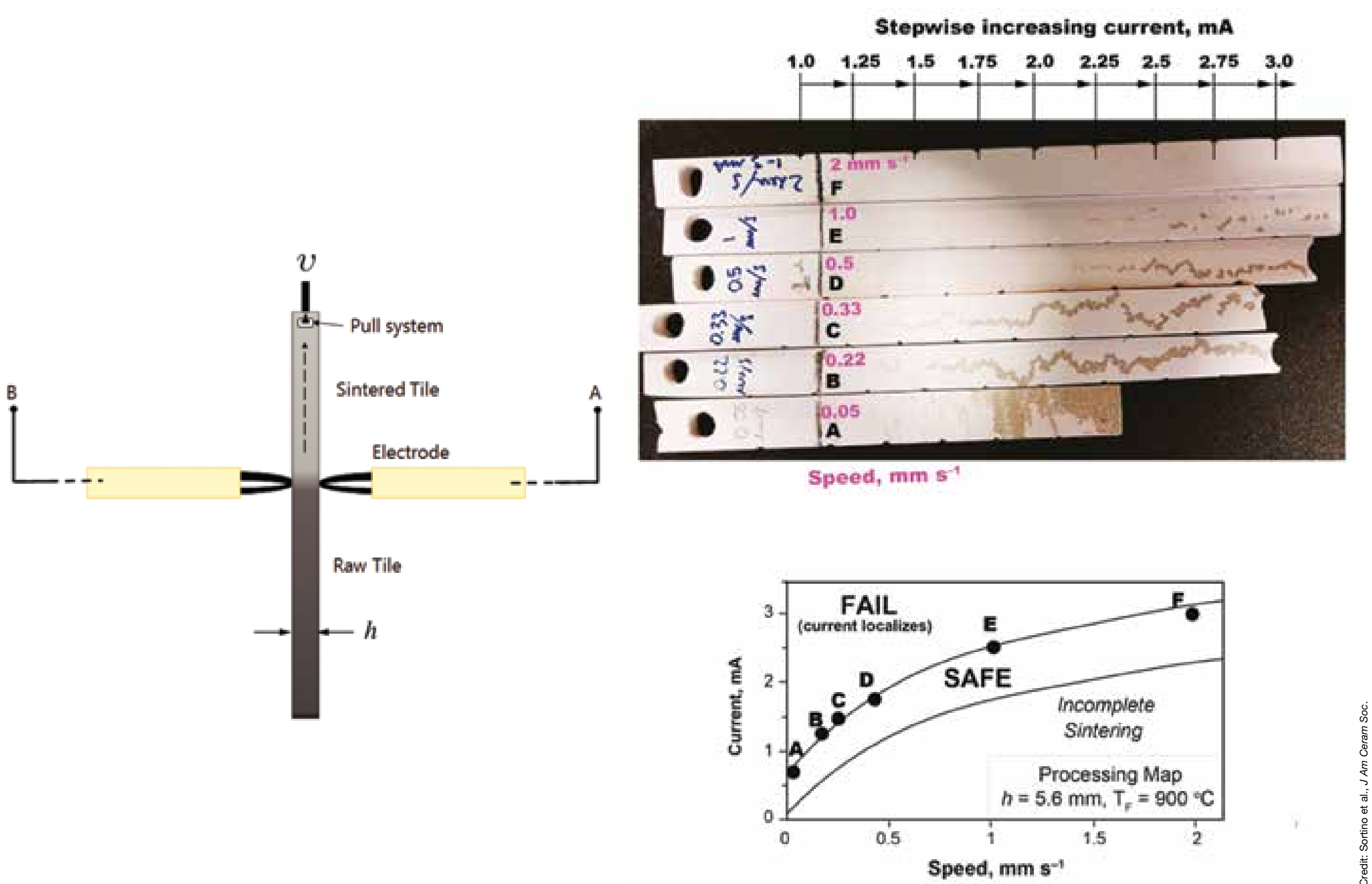


Figure 2. Experimental set-up for continuous flash experiment and processing map in terms of electric current and speed. The specimens at lower speeds show localization and defects.[24]

rent densities through the workpiece could be obtained even when the contact between the electrode and the surface of the ceramic was sporadic, without too much attention being given to obtaining a good contact. Video images of the process gave clear evidence of the formation of a plasma at the interface between ceramic and electrode, which evidently was enabling uniform current flow, acting as a pseudo floating electrode.

The idea of floating electrodes that conduct current through a plasma has been pursued in different ways. For instance, Engi-Mat, a company focused on special materials applications, developed a method to join a ceramic coating into a metal substrate using a movable ionized flame.[25, 26] An oxypropane flame induced electric current to the green ceramic coating, sintering it while joining it into the metallic substrate.

Saunders et al. (2016)[27] used the arc plasma generated by a welder with tungsten electrodes. The authors then coupled a higher electric field through this plasma, prompting electric current to flow through a sheet of B_4C. More recently, Dong et al. (2020)[28] demonstrated that a cold or nonthermal plasma obtained from dielectric barrier discharge powered by radio frequency (~700 volt-ampere power source) can promote flash sintering. A disk-shaped specimen of zirconia was placed between the plasma electrode and a grounded base electrode. An AC voltage of 2 kV at 20 kHz was deployed to strike the plasma and flow current through the specimen thickness. The plasma had a large spot-size and could be applied to workpieces 5–15 mm in diameter.

Another aspect that promotes high densities is compaction and conductivity of the ceramic powders.[22, 23, 27, 28] A recent patent[29] describes additive manufacturing of electrically conductive materials by Joule heating. In this patent, electrically conductive powder is deposited in layers within a bed of electrically insulating powder and then compacted. The electric current flowing between the bed ground and an electrode in contact with the electrically conductive powder surface sinters its path by Joule heating, while the insulating powder in the bed serves as structural support.

Incorporating the flash sintering apparatus into existing additive manufacturing technology as proposed in Beaman et al.[23] seems to be a good option to advance the technology. However, learning from recent attempts[21–23] and systems,[22–27, 29] it will be necessary to address three challenges to achieve the full potential of AM-MFS.

a) *Electrode materials and configurations*. The electrodes need to be versatile for making complex shapes. They need to sustain a uniform electric current flowing through the workpiece. If a floating configuration is adopted, the plasma at the electrode–workpiece interface must stable. The applied field, which is determined by the electrode spacing should be less than 1 or 2 kV cm^{-1}.

b) *Manufacturing science*. The sintering rate depends on the current density flowing through the workpiece. In microflash, the uniformity of the current density in small dimensions needs to be understood. The significance of a plasma to enable uniform flow of current from the tip of the electrode into surface of the workpiece remains a fundamental issue.

c) *Software for process control.* Flash sintering requires precise control of the voltage and current at the 10–100 millisecond time scale. Different electrical cycles can be used to optimize densification and microstructure evolution. Therefore, software is a critical aspect of AM-MFS.

Microflash experiments

We report microflash experiments in which sintering is confined to a small area on the surface of a powder bed. The influence of the electrode-configuration and the ceramic powder preparation was analyzed, the voltage and current signals were measured, and the microstructure was evaluated.

Two electrode-configurations are reported.

I. Floating electrode that moves along the surface of a ceramic sheet placed on top of a copper plate that serves as the ground electrode. In this case, the electric current flows between the copper plate and the electrode, producing sintering along its path.

II. A pair of electrodes placed in "casual" contact with the surface of a pressed powder bed. In this arrangement, the ceramic sintering takes place in the gap between the electrodes.

Both instances need a plasma between the tip of the electrode and the surface of the workpiece to achieve uniform current flow.

The powder-pressed sheet samples were made of 3 mol% yttria stabilized zirconia (3YSZ) powder (TZ-3Y from Tosoh, Japan) with or without the addition of 3 wt.% of silver powder (0.5–1.2 μm and 99.95% purity from Inframat Advanced Materials, USA). The powders were mixed manually using a mortar and pestle and pressed at 150 MPa into rectangular cross-sections 15 mm long, 3.5 mm wide, and 1 mm thick. Additionally, commercial 3YSZ tapes (from ESL Electro Science, USA), 0.36 mm thick and 10 mm wide (heated to burn out the binder), were used for Type I experiments; these results were similar to the powder pressed samples without silver.

The specimens were placed on the surface of a homemade heater held at 400°C. The heater assembly was mounted on a linear stage (LST 0750 from Zaber, Canada). The electric field across the samples was sustained by a 2 kV, 60 mA DC power supply (FC series from Glassman, USA). The voltage and current were measured continuously with a data acquisition device (DAQ USB 6008 from National Instruments, USA). The experiments were recorded with a CCD camera (DM51AU from The Imaging Source, USA). Linear stage, power supply, and video camera were controlled by a software developed on MATLAB.

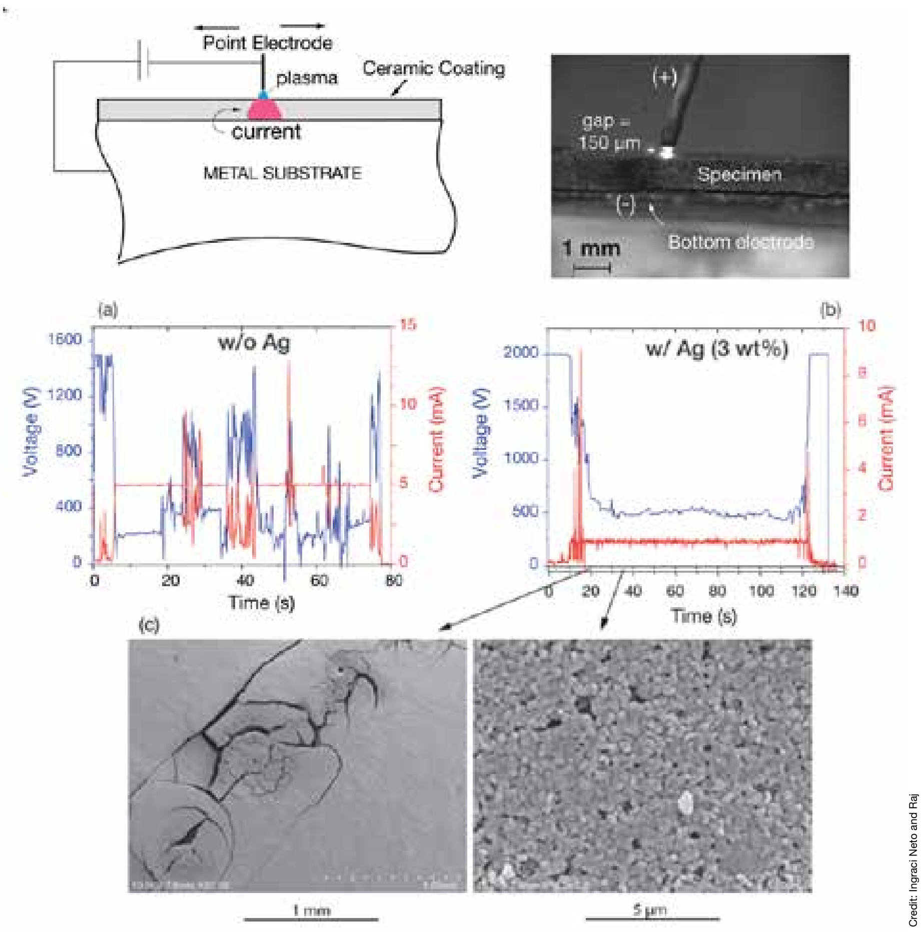


Figure 3. Type I experiments, contactless electrode. (a) The scheme. (b) Plasma formation. (c) Influence of 3 wt.% of silver on the current and voltage response. (The value of 5 wt.% in the figure on the right should have been 3 wt.%.)

The microstructure of the specimens after flash sintering was examined in a SU3500 (Hitachi, Japan) scanning electron microscope.

Figure 3 shows a scheme of Type I experiments (contactless electrode) and their results. By keeping a distance of 150 μm between the electrode and specimen surface and applying 2,000 V, the air was ionized, generating a plasma and triggering flash sintering. The electrode could then be moved at 0.1 mm s^{-1} while sintering its path. It was noted that the plasma was erratic when flashing the pure 3YSZ sheet. The addition of 3 wt.% of silver to the 3YSZ helped to stabilize the plasma, reducing by two times the electric field necessary to sustain the flash. (Plasma stability is essential to move the electrode along the surface and achieve uniform current flow through the workpiece.)

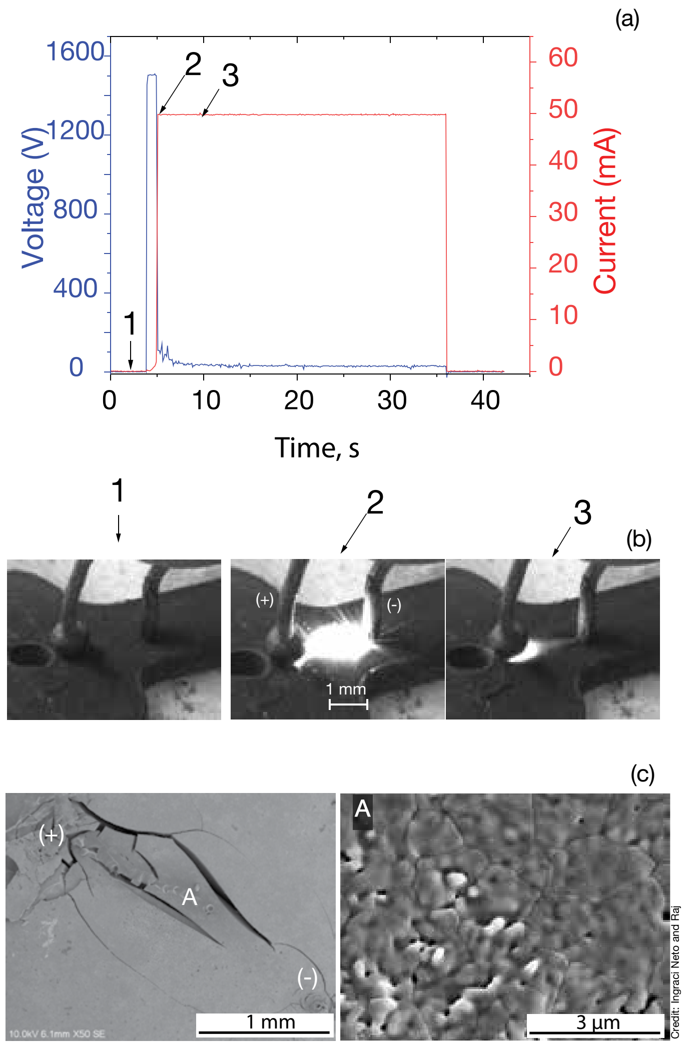


Figure 4. Type II experiments, pair of electrodes in contact with the surface of a 3YSZ specimen containing 3 wt.% silver. (a) Electric parameters. (b) Luminescence changes with time and current. (c) Micrographs of the surface after flash sintering.

Figure 4 shows Type II experiments. The pair of electrodes were placed in a "casual" contact with the sample surface; it so happened that one electrode was closer to the surface than the other. DC field with 1,500 V was applied at time (1) marked in the current profile. After the incubation time, the current rose, indicating the onset of flash (2). At this point the power supply was switched to current control to a limit of 50 mA. The light emission is from electroluminescence and plasma generation.[24] The sample was kept flashing during ~30 seconds. Less than 10 seconds after the flash onset, the luminescence concentrated near the anode (3), presumably because it was separated further away from the surface than the other electrode. Flash was stable with this electrode arrangement and promoted the densification of the material between the electrodes. However, cracks developed from shrinkage strain relative to the surrounding material, as visible in Figure 4c, because of the friable nature of the powder bed. This issue should not arise in digital buildup of a dense three-dimensional body.

Discussion and conclusions

The experiments described in Figures 3 and 4 give insights about AM-MFS.

1. Doping the ceramic powders with a metal powder, at just 3 wt.% of silver, stabilized the flash parameters. The dopant also prevented the degeneration of the plasma during the movement of the electrode by reducing the electric field necessary to sustain the flash.
2. A pair of electrodes could be used to sinter a small spot of material, an approach that could be used to incorporate flash sintering into additive manufacturing.
3. The cracks seen in Figures 3 and 4 arise from the shrinkage of the sintered spot away from the surrounding, friable material in the powder bed. However, this shrinkage would not be an issue in AM-MFS because the dense body will be built up digitally, one small spot at a time. Because the surrounding material would be dense, cracks will not form. Also, it is demonstrated that constrained sintering becomes a nonissue in flash sintering,[30] which would prevent cracking from differential shrinkage.

The role of silver addition in the experiments was to lower the field required for the onset of flash. Previous research showed that flash onset occurs at a certain level of power density,[31] which is given by the product of the second power of the electrical field and the specific conductivity of the work piece. This fact means that the field needed for flash decreases as the conductivity increases. If, however, the local temperature of the workpiece can be raised for example by focusing a small laser spot, then the addition of silver may not be necessary. A heat source would reduce the electric field intensity needed to initiate the flash.[10]

A schematic of an engine for AM-MFS is illustrated in Fig. 5. A plasma jet can be added to promote contactless electrodes. The engine can be designed as a portable standalone system that can be incorporated into various additive manufacturing systems. The spot for flash sintering is heated with the laser. (The heating source can also be a spot-heaters powered by infrared lamps; they are commercially available.) The laser and the electrodes are ganged to one another and adjusted together, in tandem, for microsintering on the surface of the workpiece.

The immediate challenge is the mechanical design and the development of software for system level control of the engine. The voltage and the current must be optimized in the time domain. Simulations and analytical models emerging from manufacturing science would be needed. (An example of such models is presented in Sortino et al.[24] for the traveling flash experiment described in Fig. 2). The engine can be evaluated iteratively with model experiments, such as those described by Figures 3 and 4.

Much work lies ahead. But progress can be rapid if emanating from fundamental scientific research in the field of flash and reactive flash sintering.

Acknowledgments

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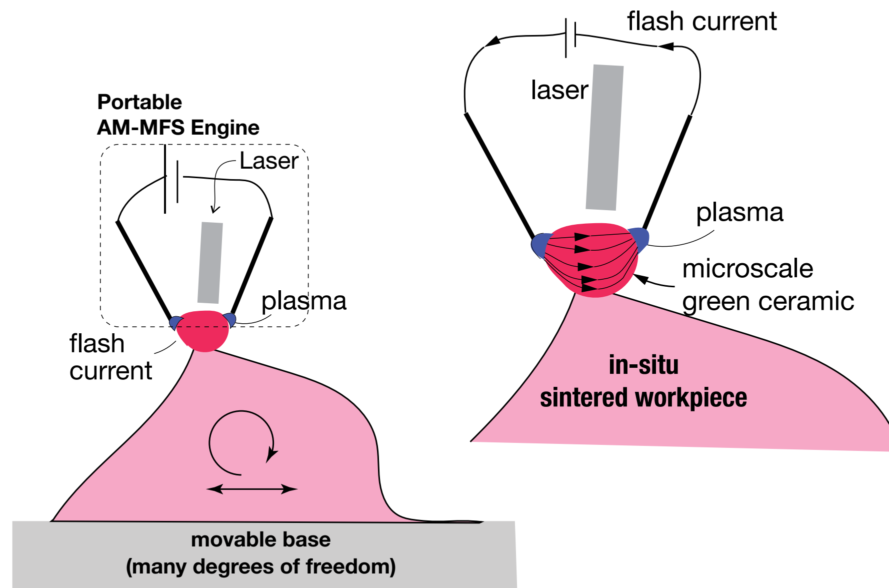

Figure 5. A stand-alone engine for microflash sintering that can be integrated into different types of additive manufacturing systems.

Credit: Ingraci Neto and Raj

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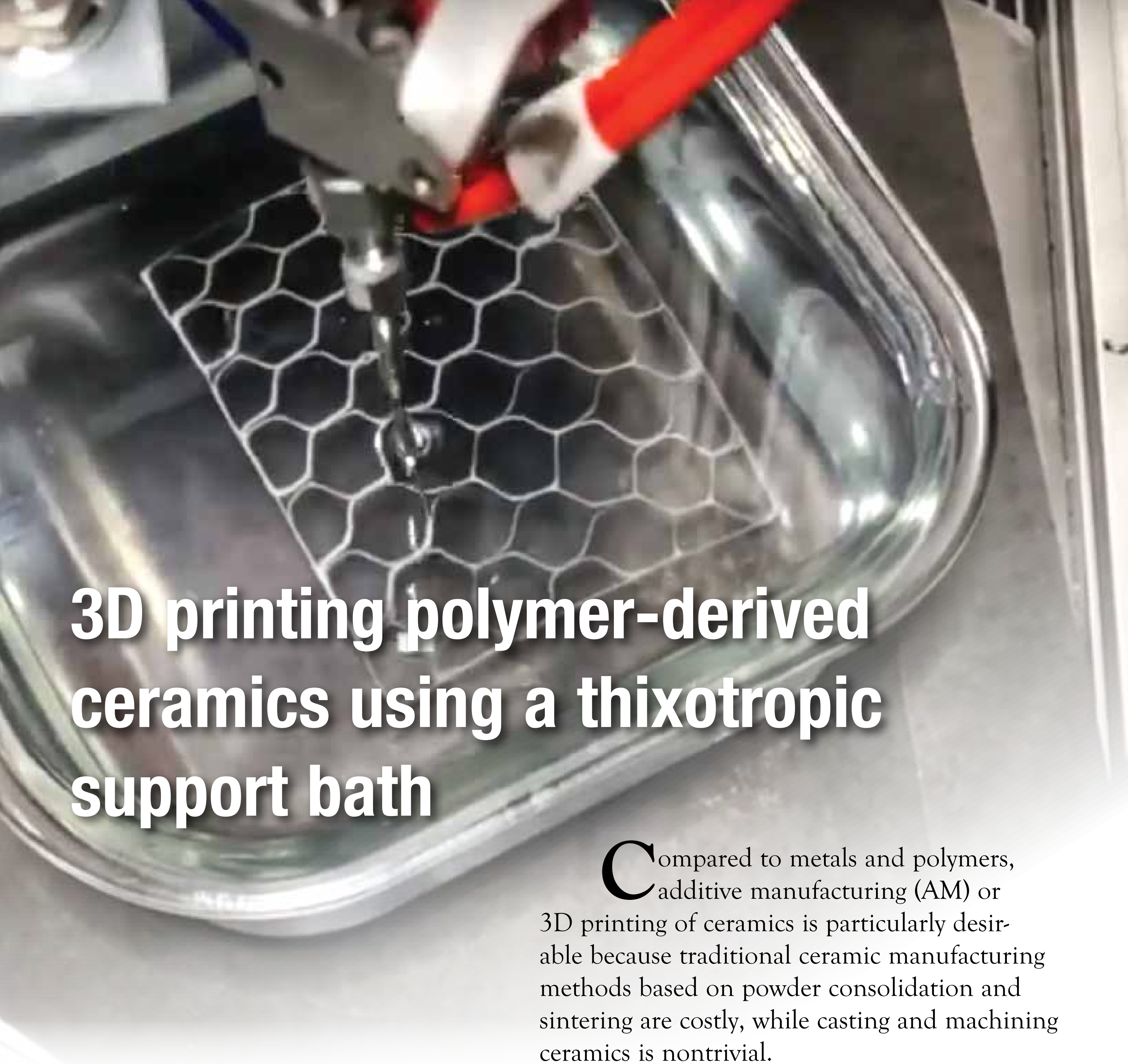

3D printing polymer-derived ceramics using a thixotropic support bath

By Majid Minary and Mohammadreza Mahmoudi

Thixotropic support baths offer a way to address several challenges with 3D printing polymer-derived ceramics to accomplish economical and effective additive manufacturing of these materials.

Compared to metals and polymers, additive manufacturing (AM) or 3D printing of ceramics is particularly desirable because traditional ceramic manufacturing methods based on powder consolidation and sintering are costly, while casting and machining ceramics is nontrivial.

There are several powder-based additive manufacturing processes for ceramics, including stereolithography (SLA), binder jetting, robocasting/direct ink writing (DIW), and laser sintering. In the SLA process, which goes back to as early as 1996,[1] a photosensitive resin containing ceramic particles (up to 60 vol%) is selectively cured.[1,2] After fabrication of the green body, the binder is removed (debinding process) by heating at about 600°C, followed by sintering at more than 1,500°C to obtain the final ceramic part. Fully dense ceramics with more than 97% of the theoretical density have been reported after sintering.[2]

In the binder jetting process, a liquid binder agent is selectively deposited onto ceramic particles.[3] In the DIW process, a colloidal composite paste of ceramic particles and binder/rheology modifiers is extruded through a nozzle in 3D.[4] In the laser sintering/melting process, the ceramic powder is selectively fused using a laser.[5,6]

These powder-based processes, which are all performed layer-by-layer, face several challenges. For one, they require a binder removal post-processing step. Removing the binder or resin leaves behind porosity, making the consolidation step (to achieve a dense 3D-printed part) difficult. In addition, most ceramics have low laser absorption, making laser-based additive manufacturing processes challenging. The laser-based processes generate large thermal gradients in 3D-printed parts, which is the driving force for crack formation. Porosity and cracks in 3D-printed ceramics result in low strength.

In contrast to powder-based additive manufacturing processes, polymer-derived ceramics (PDCs) offer another approach to 3D printing ceramics. PDCs are a class of ceramics obtained by the pyrolysis of polymer precursors, or preceramic polymers.[7,8] PDCs were introduced in the 1960s and can be used to synthesize a range of compounds, including SiC, SiOC, Si_3N_4, BN, AlN, SiCN, and SiBCN, among others. By having silicon-rich and carbon-rich nanosized domains, PDCs are stable against creep, oxidation, crystallization, or phase separation up to 1,500°C or higher temperatures.[7] The introduction of elements such as boron or aluminum into preceramic polymers can further improve properties such as high-temperature stability, creep, and oxidation resistance.[9] For these reasons, PDCs often are used for infiltration of ceramic matrix composites and synthesis of ceramic fibers, such as SiC fibers, materials which are used in harsh environment applications.

PDCs lend themselves to additive manufacturing because, in their polymer state, they are suitable for shaping via printing, and the subsequent cross-linking locks in the printed geometry. Preceramic polymers need to be cross-linked/cured to hold their shape before pyrolysis. The thermal cross-linking is often performed at temperatures higher than 120°C. The addition of catalyst often lowers the cross-linking temperature. After cross-linking, a thermoset is formed, which is capable of retaining its shape during pyrolysis. The pyrolysis temperature of PDCs is in the range of 900–1,300°C, which is lower than temperatures typically used in powder-based ceramic sintering (>1,600°C). The polymer-to-ceramic transformation is accompanied by release of volatile species (CH_4, H_2, CO_2, H_2O, and hydrocarbons) and results in shrinkage in the dimensions of the printed parts, which is typical of all preceramic polymers.

However, several manufacturing challenges must be addressed to accomplish economical and effective additive manufacturing of PDCs. These include the challenge of low viscosity preceramic polymer resin, the challenge of material purity (i.e., without additives and rheology modifiers), the challenge of "cold joints" generated in layer-by-layer printing and curing, and the scale-up challenge.

Scaling up challenge: SLA is a high-resolution process; however, it faces scale-up issues because the scale is limited by the projection and optical system. Such scale is suitable for sensors and electronic applications. However, structural and most energy applications require additive manufacturing processes that can be scaled up to centimeters or even meters.

Viscosity challenge: The preceramic polymer resins have low viscosity (10^2–10^3 cp). Hence, unless cross-linked (cured), they cannot retain their shape for direct extrusion, for example, by robocasting. But once they are cross-linked, they are not extrudable.

Preceramic polymers are available in two forms, either solid powder or polymer solution. The glass transition temperature of the solid powder preceramic polymer is well above room temperature (> 50°C). Thus, filaments made of powder preceramic polymers are rigid and cannot be made into a spool to be fed into the printing head, meaning fused deposition modeling is nontrivial for pure PDCs.

Polymer solutions made of powders melted or dissolved into a solvent can be used instead, but the viscosity of the (pure) solution is too low to hold its shape upon extrusion without any support. In the polymer solution form, so far additive manufacturing of PDCs is

3D printing of PDCs by SLA processes

Preceramic polymers functionalized by photosensitive groups grafted on their backbone can be cured by ultraviolet light. Due to the low penetration depth of UV light, this process is mostly used for fiber fabrication or microcomponents. For example, in 2015, Zanchetta et al. reported layer-by-layer SLA of SiOC ceramic microcomponents using an engineered photosensitive methylsilsesquioxane preceramic polymer.[10] The engineered preceramic precursor started from a commercially available silicone (SILRES MK) and an organically modified silicon alkoxide 3-(trimethoxysilyl) propyl methacrylate. In 2015, Eckel et al. reported additive manufacturing of PDCs via SLA and self-propagating photopolymerization techniques.[11] UV-activated preceramic monomers were obtained by incorporation of UV-sensitive side-groups (photoinitiators) to the backbone of the precursor polymer. Cross-linked polymer patterns were generated by UV light scanning, which were subsequently post-cured by thermal treatment or additional UV exposure. The printed and cured polymer was pyrolyzed to obtain virtually pore-free solid ceramic parts. In 2018, 3D nanofabrication of SiOC ceramic structures was demonstrated using two-photon lithography (2PL).[12]

There are several drawbacks to 3D printing of PDCs by SLA processes. For one, the SLA process requires specialized chemistry, which limits the range of applicable materials. Specifically, the preceramic polymer must be functionalized with photosensitive groups. Also, the ridges generated from layer-by-layer printing process on the surface of the printed ceramic parts in SLA are surface flaws and may result in stress concentration. Stress concentration in ceramics is detrimental given their low fracture toughness. Additionally, self-propagating photopolymerization is limited to periodic structures with linear features extending from the exposure surface (such as lattices and honeycombs). Finally, SLA prints 30–100 µm slices at each scan, and the achievable sample size is limited by the range of the scanner (scalability issue). 100

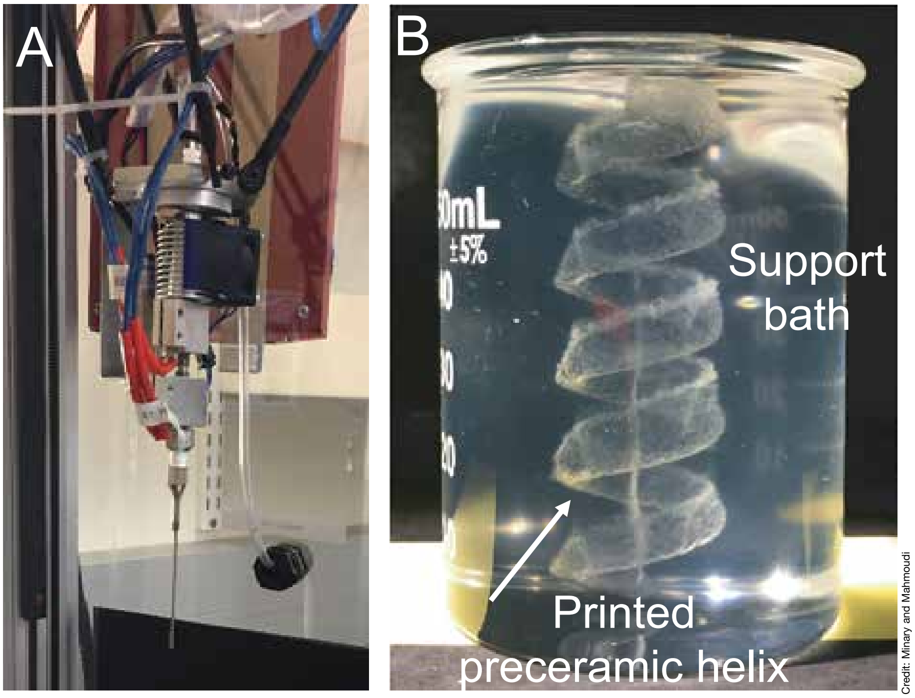

Figure 1. (A) The printhead with a long nozzle used for printing PDCs. (B) A close-up view of a helix printed inside the thixotropic bath.

only possible by photopolymerization methods (SLA and 2PL),[10–12] which make use of a limited range of photosensitive resins, limiting their scalability for many applications.

One approach to overcome the low viscosity of PDCs has been to modify the rheological properties of the resin with additives to enable extrusion through direct ink writing (DIW).[13] The rheology modifiers are expected to increase the viscosity and provide shear thinning behavior, with fast viscosity recovery, which are requirements of the DIW process. A common rheology modifier is fumed silica. However, addition of the otherwise undesirable rheology modifiers often compromises the material purity.

Cold joints challenge: "Cold joints" are generated between the previously cured layer and the newly deposited layer in layer-by-layer print-and-cure processes. For ductile materials, these joints may be tolerated. However, because ceramics are brittle (low fracture toughness), the cold joints can act as surface flaws and result in low fracture toughness through stress concentration. Hence, ideal additive manufacturing processes for PDCs should cure at "one-step" to eliminate the cold joint issue.

Thixotropic support bath: Overcoming 3D printing challenges of PDCs

Recently, a rheology modifier-and-photoinitiator free approach to additive manufacturing of PDCs was reported (Figure 1, https://www.youtube.com/watch?v=31OuaffemS4).[14] This process leverages a concept from the fluid mechanics and biomedical communities,[15,16] namely thixotropic fluids, which can switch between a solid state and a fluid state under shear stress (Figure 1B). Materials such as mayonnaise and shaving cream have this interesting behavior. Ridges and valleys on the mayonnaise surface can be observed under no stress, while mayonnaise easily flows under shearing by a knife. Similarly, a thixotropic bath behaves as a solid and holds its shape even when held upside down (in the absence of shear stress).

This class of materials show solid-to-fluid transition under shear stress. Thixotropy is defined as "a reversible, inelastic, time dependence of the viscosity or yield stress during and after flow."[17] Thixotropic materials can be considered "microstructured" fluids. When a shear stress is applied to a thixotropic material, the internal microstructure "breaks up" and results in transition to fluid (thinning). Once the shear stress is removed, the internal microstructure "builds up," which results in transition to solid "thickening." This build-up is attributed to in-flow collisions and the Brownian motion. For example, the bath viscosity can decrease by about five orders of magnitude by increasing the shear rate from 10^{-2}–10^{+3} per second. (This decrease in viscosity facilitates dispensing of the preceramic polymer into the bath.)

Most synthetic thixotropic materials are a colloidal dispersion of nanoparticles or microparticles in a liquid such as silicone oil, mineral oil, or water. In this work, the support bath was prepared by mixing 5 wt.% fumed silica (~200–300 nm) in 95 wt.% light mineral oil. The reversible solid-to-fluid transition of a thixotropic material makes it ideal as a sacrificial support for additive manufacturing of PDCs. Consider a nozzle moving in a thixotropic fluid. In this approach, the preceramic polymer is dispensed from the nozzle tip into the bath. In the vicinity of the moving nozzle and under nozzle shear stress, the thixotropic bath fluidizes. Behind the nozzle track, the bath turns to solid and supports the dispensed polymer. When a low viscosity polymer is extruded at the tip of the moving nozzle, the printed geometry is maintained stable once the thixotropic fluid returns to its solid behavior. After printing, the printed part, while still inside the bath, is cured in an oven (>120°C) in "one step" to cross-link the preceramic polymer (Figure 2B). The cross-linked polymer is retrieved from the bath and converted to ceramic by pyrolysis. Figure 2 shows several of the printed PDC structures. The printed PDC structures are SiOC, although this process can be applied to other types of PDCs.

3D printing was performed using a home-built delta-type 3D printer (Figure 1A). The preceramic polymer was dispensed into the bath using a long slender needle (diameter of 0.024 inch) under a back pressure provided by a syringe pump. The printed parts were cross-linked at once inside the same bath at about 160°C for 2 hours. The cross-linked parts were retrieved from the bath, and the pyrolysis was done inside a tube furnace at a temperature of 900°C for 1 hour.

Figure 2. Several of the printed polymer-derived ceramic structures.

In all PDCs, the release of volatile species results in shrinkage. The linear shrinkage in this work was estimated by direct measurement and found to be approximately 15%. To prevent large distortions, the printed samples should be symmetric and their surfaces should be free of support during pyrolysis to allow for uniform outgassing.

After printing, the PDCs were tested to quantify their mechanical properties. The three-point bending test revealed a strength of 232 ± 69 MPa for the printed beams. Figure 3A shows several 3D-printed ceramic beams as-printed (pre-crosslinked) inside the bath. A pyrolyzed beam under three-point bending test is shown in Figure 3B. A cross-section SEM image and an optical image of the broken sample under three-point bending test is shown in Figure 3C and D.

This manufacturing process addresses several of the challenges with 3D printing PDCs. The sacrificial thixotropic bath can support a pure and low viscosity preceramic polymer solution without any need for rheology modifiers. The "one-step" curing eliminates cold joints because each layer is printed on the uncured resin, thus making it advantageous for mechanical properties after the printing is over. The process can be readily scaled-up to larger print sizes by using gantry CNC machines or industrial robotic arms. This process is low-cost because it does not require specialized printers, and any extrusion-style printer can perform the process. The bath of conventional mineral oil and the widely available fumed silica is low-cost and reusable. Additionally, no material is wasted to print support structures and any off-the-shelf preceramic polymer can be used as-received because no specialized chemistry is required. The process is high-speed because the polymer solution is extruded and no layer-by-layer curing is required; no support material is printed, and hence there is no support material removal. Furthermore, no binder removal step is required. The bath preparation takes only a few hours and can be prepared in large containers for virtually any print size. In addition, the bath is transparent, which enables in situ process monitoring for further developments.

Given the scalability of the process, its ability to use off-the-shelf ceramic precursors, and its compatibility with low-cost extrusion printers, the process is appealing for widespread applications in industry and academia, including high-temperature structural ceramics (such as hypersonic applications), energy storage and conversion devices, and sensors for harsh environments.

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This work is supported by The Eugene McDermott Professorships at UT Dallas and partially by the U.S. National Science Foundation.

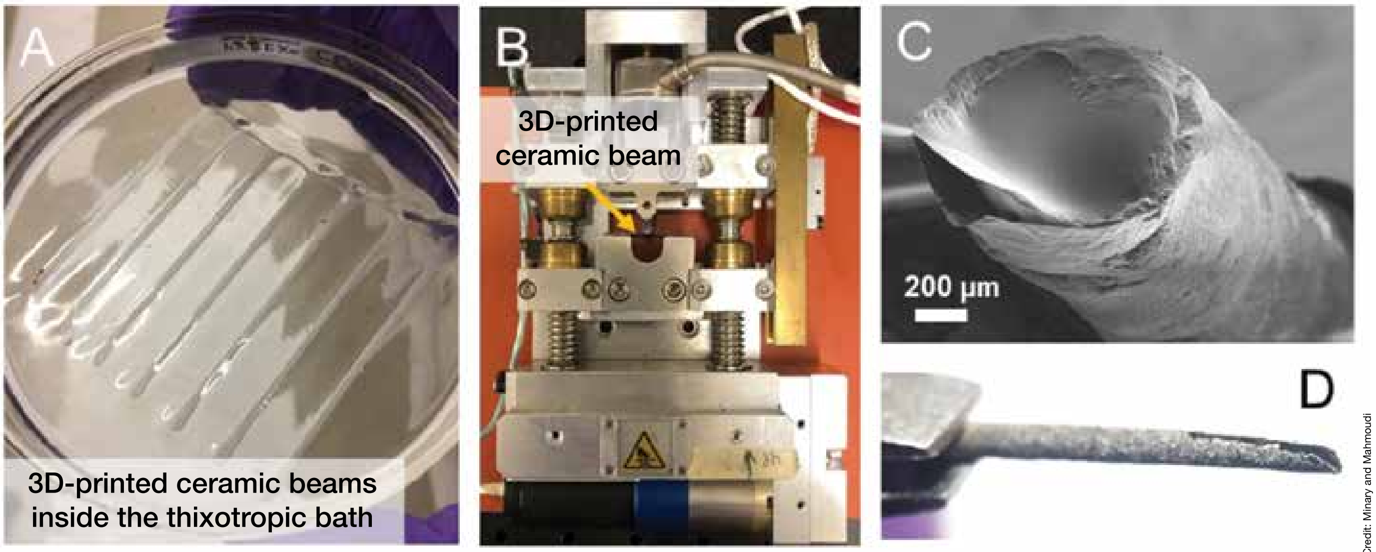

Figure 3. (A) Several 3D-printed ceramic beams inside the bath. The beams are as-printed (pre-crosslinking). (B) A pyrolyzed beam under three-point bending test. (C) A scanning electron microscope image of the cross-section of the beam after three-point bending test. (D) One piece of the broken beam after three-point bending test.

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The 45th International Conference on Advanced Ceramics and Composites covers the gamut of advanced ceramic applications

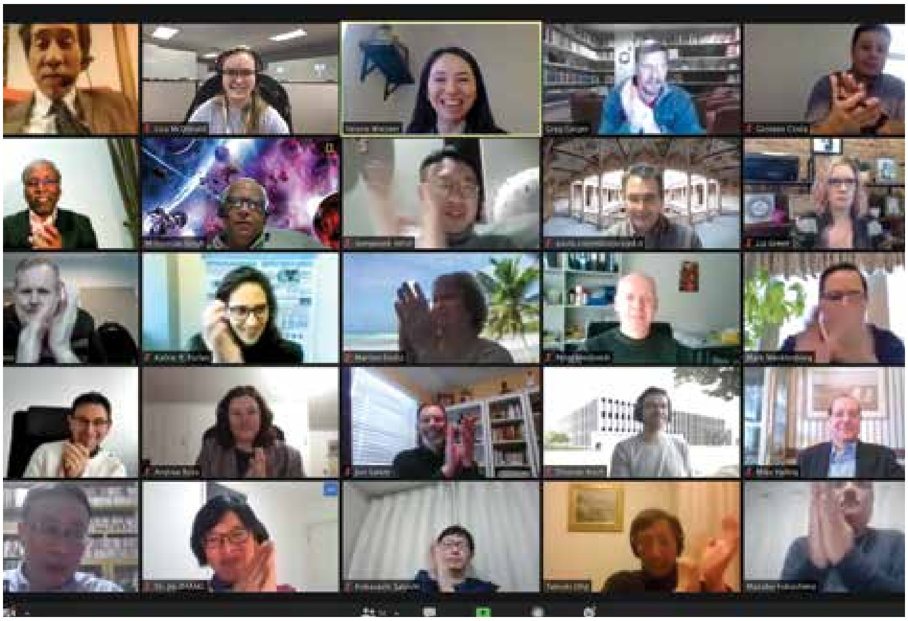
The 45th International Conference and Expo on Advanced Ceramics and Composites (ICACC 2021), which usually takes place in Daytona Beach, Fla., was held virtually on Feb. 8–11, 2021.

Excluding MS&T20, which ACerS co-hosted with two other societies, ICACC 2021 had the largest number of attendees for a virtual conference to date. The week-long conference welcomed 836 attendees, including 236 students, from 41 countries to participate in 18 symposia and four focused sessions, which featured over 680 submitted abstracts. Thirty-two live networking sessions also took place between sessions.

The four award and plenary talks that typically take place the first morning of the conference were split across two days due to the virtual format. On Monday, University of California, Davis Distinguished Professor Emeritus Zuhair Munir gave the Mueller Award lecture on the role of electric field effects in the processing of materials. His presentation was followed by plenary speaker Julia Greer, Ruben F. and Donna Mettler professor of materials science, mechanics, and medical engineering and director of the Kavli Nanoscience Institute at the California Institute of Technology, who discussed her group's research on creating 3D nanoarchitected metamaterials.

On Tuesday, Politecnico Di Torino Full Professor Monica Ferraris delivered the aptly named Bridge Building Award lecture "Joining and integration: Building bridges between materials," which discussed her work developing SiC/SiC composites for nuclear applications with collaborators in Japan, the United States, and Europe. Kyushu University Distinguished Professor Kazunari Sasaki delivered the second plenary after Ferraris' talk, and he discussed the use of ceramic materials in fuel cells and hydrogen energy production.

In addition to these talks, NASA Glenn Research Center research materials engineer Amjad Almansour gave the 10th Global Young Investigator Award Lecture while Eva Hemmer (University of Ottawa, Canada), Jessica Krogstad (University of Illinois at Urbana-Champaign), and Miki Inada (Kyushu University, Japan) delivered the third annual Jubilee Global Diversity Award lectures.


Credit: ACerS

Attendees applaud those recognized at the Engineering Ceramics Division Appreciation Session on Wednesday, Feb. 10.

Winners of the 44th ICACC student poster session were announced during the opening session of the 45th ICACC. Three posters were awarded first place: Michael Straker et al., for "Growth of high purity zone-refined boron carbide single crystals by laser diode floating zone method"; Coleman et al., for "DFT study of the impact of impurities in SiC bulk and grain boundaries"; and Bull et al., for "Atomic layer deposition of ultra-high temperature ceramics as hydrogen environmental barrier coatings for nuclear thermal propulsion."

On Wednesday, the Engineering Ceramics Division conference organizers hosted an Appreciation Session to recognize the people who helped to make ICACC 2021 possible. ECD chair Valerie Wiesner surprised chair-elect and program chair Hisayuki Suematsu with a thank-you card signed by the other organizers and attendees for his work organizing ICACC 2021. The session also recognized ACerS past president Tatsuki Ohji, for whom there will be an honorary symposium next year at ICACC 2022.

The recordings from ICACC 2021 will be available through April 12, 2021. If you did not attend the live event, you can still register at https://ceramics.org/event-subpage/icacc-2021-registration to view the almost 700 presentations.

Plan to join us next year for ICACC 2022 in Daytona Beach, Fla., Jan. 23–28, 2022. We look forward to seeing everyone in person again!

SAVE THE DATE July 19–22, 2021

LIVE VIRTUAL CONFERENCE

MATERIALS CHALLENGES IN ALTERNATIVE AND RENEWABLE ENERGY 2021 (MCARE 2021)

4TH ANNUAL ENERGY HARVESTING SOCIETY MEETING (EHS 2021)

Hosted and organized by: Energy Materials and Systems Division

The American Ceramic Society www.ceramics.org

Energy Harvesting Society

Also organized by:

KIChE The Korean Institute of Chemical Engineers

ceramics.org/mcare2021

MATERIALS CHALLENGES IN ALTERNATIVE AND RENEWABLE ENERGY (MCARE 2021), organized by

The American Ceramic Society and its new Energy Materials and Systems Division, is a premier forum to address opportunities of emerging materials technologies that support sustainability of a global society. MCARE 2021 brings together leading global experts from universities, industry, research and development laboratories, and government agencies to collaboratively interact and communicate materials technologies that address development of affordable, sustainable, environmentally friendly, and renewable energy conversion technologies. If your research seeks sustainable energy solutions on a global scale, you should attend this conference.

This cutting-edge international conference features plenary and invited talks, thematically focused technical sessions, and poster presentations, enabling participants to network and exchange ideas with professional peers and acclaimed experts. The conference atmosphere engages and promotes the participation of scientists and engineers of all ages to include students and early-stage researchers.

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4TH ANNUAL ENERGY HARVESTING SOCIETY MEETING (EHS 2021)

Since its inception, the EHS workshop has been highly successful in bringing the academic community from around the world together to openly discuss and exchange ideas about energy harvesting. Those researching energy harvesting know it has become the key to the future of wireless sensor and actuator networks for a variety of applications, including monitoring of temperature, humidity, light, and location of individuals in a building, chemical/gas sensor, structural health monitoring, and more. Join us to share your research in this area and to freely discuss and network with colleagues from around the globe interested in energy harvesting solutions.

This 4th annual meeting will feature plenary lectures, invited talks, and contributed talks within the following topical areas:

- Energy harvesting (e.g., piezoelectric, inductive, photovoltaic, thermoelectric, electrostatic, dielectric, radioactive, electrets)
- Energy storage (e.g., supercapacitors, batteries, fuel cells, microbial cells)
- Applications (e.g., structural and industrial health monitoring, human body network, wireless sensor nodes, telemetry, personal power)
- Emerging energy harvesting technologies (e.g., perovskite solar cells, shape memory engines, CNT textiles, thermomagnetics, bio-based processes)
- Energy management, transmission, and distribution; energy-efficient electronics for energy harvesters and distribution
- Fluid-flow energy harvesting
- Solar–thermal converters
- Multi-junction energy harvesting systems
- Wireless power transfer

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PACRIM14 will provide a unique forum for knowledge exchange and sharing, and facilitate the establishment of new contacts from all over the world. The technical program will cover a wide range of exciting and emerging topics organized into a seven-track system, which includes 42 symposia planned that will identify global challenges and opportunities for various ceramic technologies.

TRACKS

Multiscale Modeling, Simulation, and Characterization

- **S1:** Characterization and modeling of ceramic interfaces: Structure, bonding, and grain growth
- **S2:** Frontier of modeling and design of ceramics and composites
- **S3:** Advanced structure analysis and characterization of ceramics

Innovative Processing and Manufacturing

- **S4:** Novel, green, and strategic processing and manufacturing technologies
- **S5:** Polymer derived ceramics (PDCs) and composites
- **S6:** Advanced powder processing and manufacturing technologies
- **S7:** Synthesis, processing, and microstructural control of materials using electric currents, magnetic fields, and/or pressures
- **S8:** Porous ceramics: Innovative processing and advanced applications
- **S9:** Additive manufacturing and 3D printing technologies
- **S10:** Sol-gel processing and related liquid-phase synthesis of ceramics
- **S11:** Layered double hydroxides: Science and design of binding field with charged layers
- **S12:** Specific reaction field and material fabrication design

Nanotechnology and Structural Ceramics

- **S13:** Novel nanocrystal technologies for advanced ceramic materials and devices
- **S14:** Functional nanomaterials for energy harvesting and solar fuels
- **S15:** Engineering ceramics and ceramic matrix composites: Design, development, and applications
- **S16:** Advanced structural ceramics for extreme environments
- **S17:** Multifunctional coatings for structural, energy, and environmental applications
- **S18:** Advanced wear resistant materials: Tribology and reliability
- **S19:** Geopolymers: Low energy and environmentally friendly ceramics

Multifunctional Materials and Systems

- **S20:** Multiferroic materials, devices, and applications
- **S21:** Crystalline materials for electrical, optical, and medical applications
- **S22:** Microwave dielectric materials and their applications
- **S23:** Transparent ceramic materials and devices

Ceramics for Energy Systems

- **S24:** Solid oxide fuel cells and hydrogen technologies
- **S25:** Direct thermal to electrical energy conversion materials, applications, and thermal energy harnessing challenges
- **S26:** Materials for solar thermal energy conversion and storage
- **S27:** Advanced materials and technologies for electrochemical energy storage systems
- **S28:** Atomic structure and electrochemical property diagnosis toward full crystal rechargeable batteries
- **S29:** Ceramics and ceramic matrix composites for next generation nuclear energy
- **S30:** High temperature superconductors: Materials, technologies, and systems

Ceramics for Environmental Systems

- **S31:** Advanced functional materials, devices, and systems for environmental conservation, pollution control, and critical materials
- **S32:** Ceramics for enabling environmental protection: Clean air and water
- **S33:** Photocatalysts for energy and environmental applications
- **S34:** Glass and ceramics for nuclear waste treatment and sequestration

Biomaterials, Biotechnologies, and Bioinspired Materials

- **S35:** Advanced additive manufacturing technologies for bio-applications; materials, processes, and systems
- **S36:** Advanced multifunctional bioceramics and clinical applications
- **S37:** Material and technology needs for medical devices, sensors, and tissue regeneration
- **S38:** Nanotechnology in medicine
- **S39:** Biomimetics and bioinspired processing of advanced materials

Special Topics

- **S40:** 6th International Richard M. Fulrath Symposium, "Frontiers of ceramics for a sustainable society"
- **S41:** Advancing the global ceramics community: fostering diversity in an ever-changing world
- **S42:** Young Investigator Forum: Next-generation materials for multifunctional applications and sustainable development, and concurrent societal challenges in the new millennium

Calendar of events

March 2021

24–25 56th Annual St. Louis Section/Refractory Ceramics Division Symposium on Refractories – VIRTUAL EVENT ONLY, presented live; https://ceramics.org/event/56th-annual-st-louis-section

24–29 ➨ 2nd Global Forum on Smart Additive Manufacturing, Design and Evaluation (SmartMADE) – Osaka University, Nakanoshima Center, Japan; http://www.jwri.osaka-u.ac.jp/~conf/Smart-MADE2021

27–31 ➨ The Int'l Conference on Sintering 2022 – Nagaragwa Convention Center, Gifu, Japan; https://www.sintering2021.org

April 2021

7–8 ACerS-MRS Bioceramics Virtual Workshop: Potential and Challenges in Bioceramics – From Fundamental Research to Clinical Translation – VIRTUAL EVENT ONLY; https://ceramics.org/acers-mrs-bioceramics-workshop

25–30 ➨ International Congress on Ceramics (ICC8) – Bexco, Busan, Korea; www.iccs.org

27–28 Glass International Digital Forum – VIRTUAL EVENT ONLY; https://www.glass-international.com/glass-international-digital-forum

May 2021

3–7 6th International Conference on Competitive Materials and Technology Processes (ic-cmtp6) – Hunguest Hotel Palota, Miskolc-Lillafüred, Hungary; www.ic-cmtp6.eu

16–19 ➨ Ultra-high Temperature Ceramics: Materials for Extreme Environment Applications V – The Lodge at Snowbird, Snowbird, Utah; http://bit.ly/5thUHTC

June 2021

22–23 ceramitec conference 2021 – Messe München; Munich, Germany; https://www.ceramitec.com/en/trade-fair/ceramitec-conference

28–30 MagForum 2021: Magnesium Minerals and Markets Conference – Grand Hotel Huis ter Duin, Noordwijk, Amsterdam; http://imformed.com/get-imformed/forums/magforum-2020

July 2021

19–22 Materials Challenges in Alternative & Renewable Energy 2021 (MCARE 2021) combined with the 4th Annual Energy Harvesting Society Meeting (EHS 2021) – VIRTUAL EVENT ONLY, presented live; https://ceramics.org/mcare2021

August 2021

31–Sept 1 6th Ceramics Expo – Cleveland, Ohio; https://ceramics.org/event/6th-ceramics-expo

September 2021

14–17 17th Biennial Worldwide Congress Unified International Technical Conference on Refractories – Hilton Chicago, Chicago, Ill.; https://ceramics.org/unitecr2021

October 2021

12–15 ➨ International Research Conference on Structure and Thermodynamics of Oxides/carbides/nitrides/borides at High Temperature (STOHT) – Arizona State University, Ariz.; https://mccormacklab.engineering.ucdavis.edu/events/structure-and-thermodynamics-oxidescarbidesnitridesborides-high-temperatures-stoht2020

17–21 ACerS 123rd Annual Meeting with Materials Science & Technology 2021 – Greater Columbus Convention Center, Columbus, Ohio; https://ceramics.org/mst21

18–20 Flourine Forum 2021 – Pan Pacific Hanoi, Vietnam; http://imformed.com/get-imformed/forums/fluorine-forum-2020

25–27 China Refractory Minerals Forum 2021 – InterContinental, Dalian, China; http://imformed.com/get-imformed/forums/china-refractory-minerals-forum-2020

November 2021

1–4 ➨ 82nd Conference on Glass Problems – Greater Columbus Convention Center, Columbus, Ohio; http://glassproblemsconference.org

December 2021

12–17 14th Pacific Rim Conference on Ceramic and Glass Technology (PACRIM 14) – Hyatt Regency Vancouver, Vancouver, British Columbia, Canada; www.ceramics.org/PACRIM14

January 2022

18–21 Electronic Materials and Applications 2022 (EMA 2022) – DoubleTree by Hilton Orlando at Sea World Conference Hotel, Orlando, Fla; https://ceramics.org/ema2022

23–28 46th International Conference and Expo on Advanced Ceramics and Composites (ICACC2022) – Hilton Daytona Beach Oceanfront Resort, Daytona Beach, Fla.; https://ceramics.org/icacc2022

July 2022

24–28 Pan American Ceramics Congress and Ferroelectrics Meeting of Americas (PACC-FMAs 2022) – Hilton Panama, Panama City, Panama; https://ceramics.org/PACCFMAs

Dates in **RED** denote new event in this issue.

Entries in **BLUE** denote ACerS events.

➨ denotes meetings that ACerS cosponsors, endorses, or otherwise cooperates in organizing.

denotes virtual meeting

Ceramic & Glass MANUFACTURING

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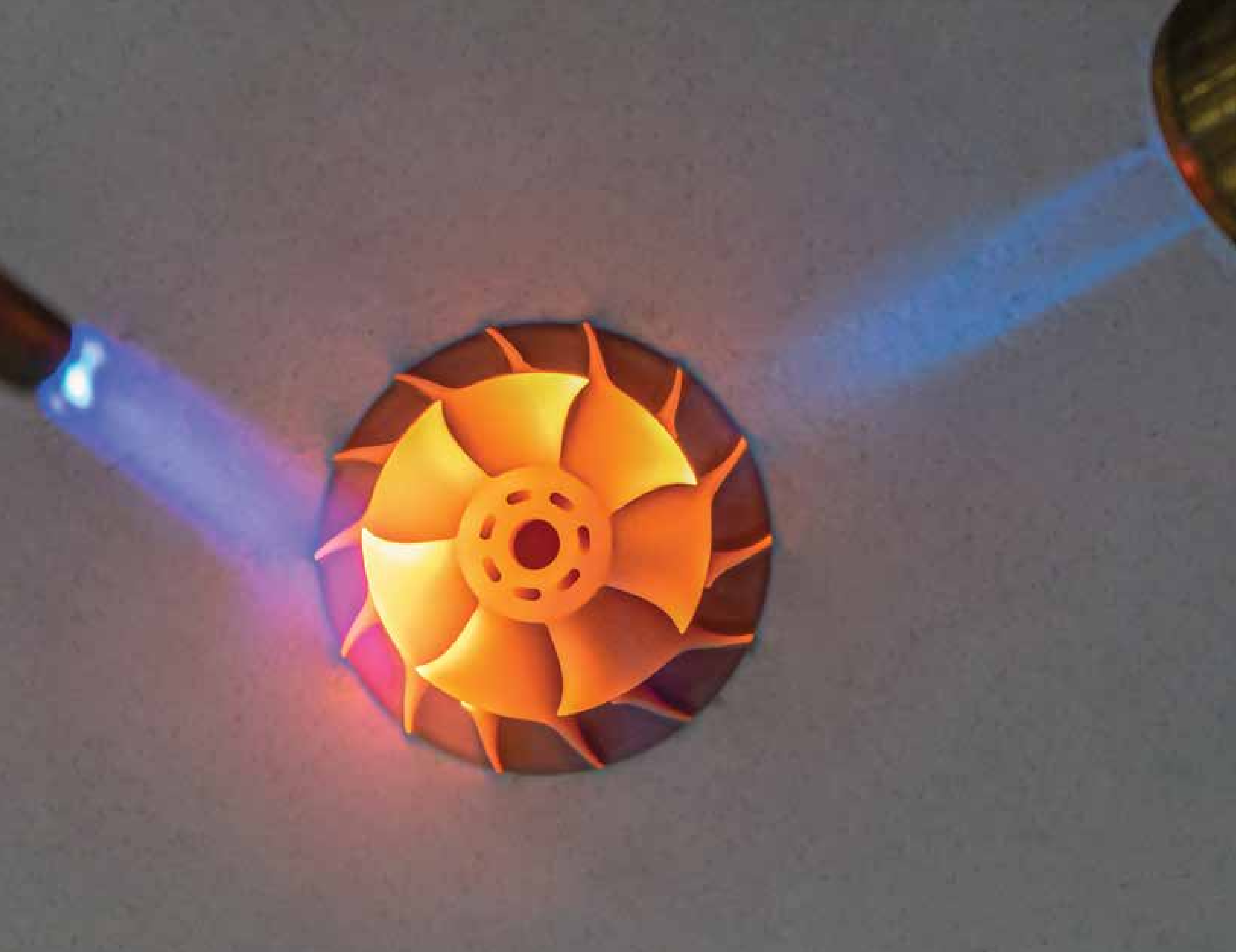

A BRIGHT AND BOLD FUTURE AHEAD: HOW CERAMIC ADDITIVE MANUFACTURING IS DRIVING GROWTH

THE PROMISING PATH FORWARD FOR ADDITIVELY MANUFACTURED CERAMICS

ALFRED UNIVERSITY-CACT PARTNERSHIP SUPPORTS LAUNCH OF START-UP COMPANY AT INCUBATORWORKS

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INDUSTRY NEWS

SCHOTT EXPANDS PHARMACEUTICAL GLASS OPERATION

Specialty glass manufacturer SCHOTT plans to build a second melting tank for pharmaceutical glass tubing at its main plant in Mainz, Germany. The investment amounts to 40 million euros. The facility is scheduled to go into operation in mid-2022. SCHOTT said it is responding to increasing global demand for glass tubing for pharmaceutical packaging. The manufacturer significantly expanded its production capacities for pharmaceutical tubing in Asia in the fall of 2020 with the commissioning of another tank in India and a new plant in China.

SCHOTT AG is based in Mainz, Germany

The Center for Glass Innovation will be a research resource for glass producers.

ALFRED CENTER FOR GLASS INNOVATION AIMS TO IMPROVE RECYCLING MARKET

The state of New York announced a collaboration with the State College of Ceramics at Alfred University to strengthen markets for recycled glass and improve the quality of glass available for recovery. The Center for Glass Innovation will be a resource for glass producers and will create space for basic and applied research, user facilities, and experimental glass tanks for applied, industrial-scale research, with an emphasis on creating higher-value end markets for curbside collected glass. This center will be the first of its kind in the United States, where glass companies will be able to test small batches of new glass compositions in a pilot production environment.

KYOCERA R&D CENTER SLATED TO OPEN IN FALL 2022

Kyocera announced the construction of a research and development center at its Kokubu campus in Kirishima City, Kagoshima, Japan. The center will focus on innovations in information and communications, environmental preservation, and smart energy. The Kokubu campus is the site of three R&D groups: Kyocera's Monozukuri R&D Laboratory, which focuses on advanced material technologies; its Production Technology Division, focusing on manufacturing process innovation; and its Analysis Center, which develops simulation and evaluation technologies. Kyocera said the investment is approximately 10 billion yen (approximately $96 million), and the facility should open in September 2022.

A rendering of the new R&D center.

CERAMICS EXPO SCHEDULED FOR AUGUST

The 2021 Ceramics Expo is scheduled to be held in person Aug. 30 to Sept. 1 at the Huntington Convention Center in Cleveland, Ohio. The theme will be "Advanced Ceramics: Enabling a Clean, Efficient and Electrified Future." Event organizers revised the format to follow physical distancing guidelines, increase aisle widths, and reduce wait time for registrations. Updates and free registration are available at www.ceramicsexpousa.com.

Total wants to reach 35 GW of production capacity from renewable sources by 2025.

TOTAL CREATES JOINT VENTURE TO DEVELOP CLEAN ENERGY IN THE US

Global energy company Total and 174 Power Global, a wholly owned affiliate of Hanwha Group, signed an agreement to form a 50-50 joint venture to develop 12 utility-scale, solar, and energy storage projects of 1.6 gigawatts cumulative capacity in the United States, transferred from 174 Power Global's development pipeline. The first project started production in 2020, and the remainder will be put on stream between 2022 and 2024. The projects will be in Texas, Nevada, Oregon, Wyoming, and Virginia. Total said it is building a portfolio in renewables and electricity that could account for up to 40% of its sales by 2050.

US DEPARTMENT OF DEFENSE FUNDS RARE EARTHS PLANT

Lynas Rare Earths Limited entered into an agreement with the U.S. Department of Defense to build a commercial light rare earths separation plant in the U.S., through its Lynas USA LLC subsidiary. Lynas said DOD funding is expected to be capped at approximately $30 million, and Lynas also will be expected to contribute approximately $30 million. The plant is expected to be located in Texas. Once operational, it is expected to produce approximately 5,000 tons per year of rare earths products. "COVID-19 has exposed the risks within global supply chains of the single sourcing of critical materials," says Lynas CEO Amanda Lacaze.

Lynas CEO Amanda Lacaze

CoorsTek participated in a traditional Thai blessing to break ground on the new facility.

COORSTEK EXPANDS IN THAILAND

CoorsTek is expanding its manufacturing footprint in southeast Asia, beginning construction on the first phase of a 400,000-square-foot engineered ceramics manufacturing facility in Rayong, Thailand. CoorsTek said it expects the facility to be fully operational by early 2022. The company will hire approximately 300 employees over the next two years, and up to 600 within five years. "We are expanding our operations into regions with better access to growing markets," says Michael Coors, co-CEO of the Colorado-based company.

MORE INDUSTRY NEWS

MURATA COMPLETES ELECTRODE MANUFACTURING PLANT

Murata Manufacturing Co., Ltd. completed a new production building at its Yasu Division in Shiga, Japan. The facility was constructed to increase the production capacity of electrode materials in order to meet medium- to long-term increases in demand, the company says. The cost of the facility was 14 billion yen (approximately $133 million). Murata designs, manufactures, and sells ceramic-based passive electronic components, communication modules, and power supply modules.

Workers will produce electrode materials at the new facility.

Peter Morten, CEO of STC, left, and Dr. Rick Yoon, former CEO & owner of IJ Research.

SUPERIOR TECHNICAL CERAMICS GROWS WITH ACQUISITION

Superior Technical Ceramics acquired Santa Ana, Calif.-based manufacturer IJ Research. IJ Research specializes in applications that include electrical feedthroughs and opto-electronic windows, along with various sapphire-to-metal brazed hermetic assemblies. The firm provides conceptual design, research and development, materials selection consulting, and prototyping through to manufacturing. STC, based in St. Albans, Vermont, is a privately owned company with more than 100 employees.

VELCO CELEBRATES 50 YEARS

For 50 years VELCO GmbH/Germany has served the foundry, steel, and refractory industries.

The company was established in 1971 by Kurt Wolf, father of today's owner Christian Wolf, in the city of Velbert located at the border of the Ruhr industrial area. Velco's first Rotamat rotor gunning machine was launched that same year, and there are almost 1,300 in use around the world today.

Over the decades, VELCO improved and broadened its machines, respecting industry's demand for cost savings, improved efficiencies, and rising safety. Besides the Rotamat, VELCO's delivery program now comprises pressure vessel gunning machines and gunning robots for the refractory repair of the different aggregates.

VELCO built up a second business line for the pneumatic transport of dry bulk materials. In steel plants, this transport mainly involves the injection of carbon or lime for slag foaming in the EAF. Other areas are secondary metallurgy or the injection into the blast furnace.

Developments continue for improving dry gunning regarding quality and dust creation as well as implementing industry 4.0 technologies. A remote access module that allows for worldwide connection using only a smartphone is available for all machines and can access data such as operation hours, flow rates, water pressure, operational conditions, fault messages, and even the location of the machine.

For further information, visit www.velco.de.

A BRIGHT AND BOLD FUTURE AHEAD: HOW CERAMIC ADDITIVE MANUFACTURING IS DRIVING GROWTH

By Alice Elt and Isabel Potestio

As the global leader in the field of industrial additive manufacturing for ceramics, Lithoz has constantly pushed the boundaries of innovation since its founding in 2011. Based in Vienna, Austria, Lithoz's mission is to grow ceramic 3D printing as a reliable manufacturing technology for industrial production, and many of our customers are now using additive manufacturing (AM) as an established production method to meet industrial standards. We have become market and technology leaders with a wide range of 3D printers, ceramic materials, and training programs in use worldwide, including in Asia, Australia, and Brazil, while the founding of a subsidiary in the United States has allowed us to better connect with customers and strengthen our global presence.

THE TIME IS NOW—THE GROWTH OF 3D PRINTING

In a world that is becoming ever more digital, ceramic 3D printing is quickly growing into an established production technique. The fact that 25% of Lithoz customers have invested in multiple additive manufacturing systems highlights the success they have had with this technology. They believe AM to be a growing manufacturing market—and they are not the only ones. A recent SmarTech Analysis study showed that the additive manufacturing industry is expected to grow over the next decade to become a $4.8 billion market by 2030,[1] with the area of technical applications representing the most significant sector for driving market growth to more than $3 billion. The adoption of ceramic AM is expected to rapidly increase, with the main inflection point being in 2025 as major ceramic AM technologies come to maturity and benefit from having enough of a presence in the market to support the serial production of final components. Figure 1 shows growth trends expected for materials and applications.[2]

Many early adopters of ceramics AM are now up to eight years ahead in terms of AM experience, giving them a significant business advantage, while the fact that customers are now using 3D-printed parts means that suppliers offering 3D printing are quickly surpassing those who do not. Finally, as the technology becomes more well-known, the range of applications is broadening—new players in various fields are entering the ceramic AM market, finding new applications in the process and innovating past traditional ceramic companies. This innovation puts them at a great advantage, allowing them to explore new design ideas and functionalities unachievable using conventional forming techniques.

Additionally, additive manufacturing gives businesses a secure supply chain in a way other production methods simply cannot. This independence has made AM invaluable for many companies during the pandemic, as they could be self-reliant in times of economic and manufacturing uncertainty. The entire AM method is modeled after digital independence—once a customer has a digital file of the part, components can be produced and edits made to reach certain parameters, and files can be saved and accessed anywhere in the world. Where there is a 3D printer, this part can now be produced. The use of digital files opens up an entire digital warehouse for the customer, making it easy to gain new connections and innovate with others in their field.

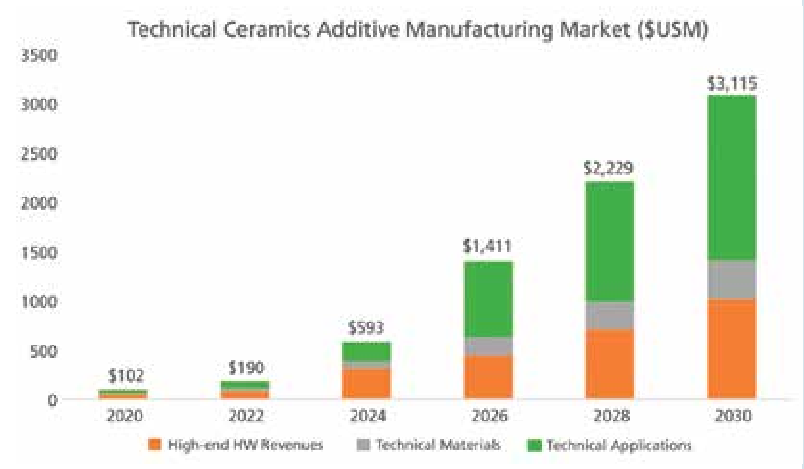

Figure 1. The rapid growth of the technical ceramics market in 3D printing. (Reference 2)
Credit: Anusci, 3D Printing Media Network

Figure 2. Lithoz 3D-printed silicon nitride. Ceramic 3D printing can print parts that might be too costly or impossible to produce using traditional manufacturing. *Credit: Lithoz*

Ceramic 3D printing is very well suited to modern manufacturing and development, no matter what field a company is based in, and the market will grow rapidly as more businesses implement AM as a serial production method to find new, innovative applications and enjoy the advantages of digitalization and a stable supply chain.

THE ADVANTAGES OF CERAMIC 3D PRINTING

As we have seen, ceramic additive manufacturing will undergo a huge period of growth in the next decade as customers take advantage of 3D printing technologies, making huge waves in the manufacturing market and disrupting traditional manufacturing processes. However, when considering the fact that there are already many well-established and conventional manufacturing methods available for ceramics, the question is: Why is another technology needed?

The reason lies in the development of today's increasingly complex and customized applications. Customers demand ever more from their technology and, as manufacturing environments develop further, demand grows for more complex components to be rapidly produced, while new ideas for applications require more freedom in design to be made a reality (Fig. 2).

When it comes to conventional forming methods, such as milling, pressing, and injection molding, companies are often limited to designing parts that can be produced, instead of parts they want to produce. The design freedom offered by 3D printing is, in this area, simply unparalleled, allowing designers to focus more on functionality when coming up with new concepts. As Ing. Tassilo of Fraunhofer IKTS states, the manufacture of "extremely complex-shaped or individualized components ... has primarily been occupied by AM" so far.[3] Using AM, it is possible to construct unique geometries, unachievable using traditional methods, and this ability greatly expands the range of possible applications for businesses in all fields. As such, Lithoz's ceramic 3D printing is an enabling technology for customers that can keep pace with even their most innovative ideas. While conventional technologies have reached their limits in terms of fulfilling modern aims, AM has grown and become a strong industry that can be used for such projects.

Another reason for implementing AM is the fact that this technology greatly speeds up the entire product development process, resulting in a shorter time to market. Design changes can be made more quickly and easily, which encourages the improvement of existing products, while the rapid production of prototypes facilitates entry into new markets. The speed of the entire process enables a quick start to exchanges between businesses and potential customers. Trend forecasters predict that customers in the future will want technology that facilitates hyper-customization, meaning that products can be rapidly altered without complication. Using AM, new designs can be created without losing the original form simply by altering digital files. This opportunity is a great one for companies to use AM to extend or change their business models and enable profitable mass customization.

Figure 3. Lithoz is known for its high-resolution and accurate technology, which is trusted for even the most precise of applications, such as these surgical tool components. *Credit: Lithoz*

One significant advantage of AM is that it does not require any set-up costs. The tooling required for traditional manufacturing processes not only has a negative impact on a part's time-to-market, but also makes such processes costly for small- or medium-sized production runs. AM technology makes small- and medium-sized runs more economical, while the fact that customers can use AM to specifically customize their designs enables easy improvements and further innovation in product design, as customers have no cost or time worries.

Take this electrosurgical tool (Fig. 3) as an example. Used in precise medical applications, this component is characterized by its extremely small size, complex internal geometry, and challenging features—aspects which are very difficult to achieve using traditional molding technologies, and which would require expensive and time-consuming tooling. However, as tooling is not required using AM, this part can be produced quickly and economically, while still ensuring that the exact form requirements are met.

HOW CERAMICISTS CAN LEVERAGE THEIR KNOW-HOW WHEN SETTING UP 3D PRINTING PROCESSES

In terms of materials, ceramicists are at a great advantage when implementing AM. This advantage is due to ceramic AM being very similar to other ceramic manufacturing processes—in terms of actually implementing 3D printing, thermal post-processing is essentially unchanged. Only the product designs need reworking, and prior ceramic experience and knowledge can still be used for the second step of the process. Furthermore, 3D printing gives ceramic businesses another option when it comes to forming technologies. Ceramics are known as being rather difficult to process in comparison to other materials, and having a new forming process alongside machining or pressing enables new ceramic applications. By adopting 3D printing, ceramicists put themselves at a great advantage to beat competitors still solely using conventional forming methods, and they can now work with difficult-to-process materials such as silicon nitride.

Overall, ceramic industries can greatly benefit from implementing AM. This technology can be used as a single manufacturing platform for everything from prototyping and small-batch production up to mass manufacturing, opening the door to a myriad of manufacturing possibilities that businesses may not have had access to before.

At Lithoz, we have already seen the success with which many different companies have implemented ceramic additive manufacturing into their production environments and how they have been able to innovate even further as a result. One company that has already taken advantage of AM is technical ceramic producer Ceramco (Fig. 4), who has been working with Lithoz's technology since 2015 and has doubled its 3D printing production capability. Thomas Henriksen, president and CEO of Ceramco, describes how the company originally implemented AM for cheaper prototyping before realizing its full potential: "Since we make parts by ceramic injection molding (CIM), we initially thought 3D printing would be a good way to give customers prototypes if they didn't want to pay for any CIM tooling. However, it turned out that many additive customers remained as additive customers, and seldom went to serial production that required CIM."

After seeing the success of AM with businesses, Ceramco decided to invest in this technology. "More often than you might think, customers persistently want additively made parts, even over conventionally made parts," Henriksen says. As leading ceramic part producers, Ceramco's experience has been that "with the right parts of ideal sizes, Lithoz 3D printing technology can be used to make very good quantities."

Figure 4. President and CEO of Ceramco Thomas Henriksen stands with the Lithoz 3D printer CeraFab 7500. *Credit: Ceramco*

As Ceramco was so far ahead of the curve in terms of investing in this technology, it is well-trained in working with this process. "We were considered an early adopter by purchasing our first machine in 2015, long before any other technical ceramic manufacturers in the U.S. invested in a machine," Henriksen says. Early investment in additive manufacturing allowed Ceramco to innovate beyond other ceramic companies, becoming leaders in the field and benefiting from the economical and effective aspects of 3D printing.

HOW AM IS DRIVING INNOVATION IN MULTIPLE MARKETS

It is now clear that AM excels in applications where injection molding, milling, and pressing cannot. But where are businesses benefiting the most? It is areas such as medical devices, the semiconductor industry, machinery, electronics, and dental components that are most driving the growth of ceramic 3D printing. Ceramco found that since AM allows for the printing of such complex structures, this technology encourages and enables the production of interlocking ceramic components that contain more features than an injection molded part. Such parts can have multiple functionalities in varying industries, thus benefiting the entire ceramic industry and meaning that components "are not necessarily market specific." Henriksen believes that ceramic AM "will give people access to ceramics much more readily, which I think will spur innovation in finding new applications."

AM has great uses in the aerospace and industrial gas turbine industries, where the freedom offered is being used to develop new designs for casting cores with more complex structures than ever before, including multiple walls and fine branches (Fig. 5). These new forms cannot be produced using conventional injection molding methods, showing how AM has greatly expanded applications in this area in ways that other technologies could not.

Developments in AM opened the door to applications far beyond technical parts. It is now possible to manufacture components for medical and dental applications, with the material properties of ceramics coming into their own in terms of biocompatibility. Additive manufacturing is being used to serially produce surgical tools in lot sizes of up to 10,000 parts, while dental parts and bone implants can be efficiently produced and expertly customized simply by editing the digital file. This ability means that medical components and implants can be matched to individual patients and certain properties modified to best suit the situation. In these fields, CE-certified Medical Devices (Class III) and FDA-approved Medical Devices (Class IIa) have already been successfully produced, used, and implanted in vivo.

Redesigning allows for improvements and new products to become fully customizable, while the entire process is made more economical and cost-effective due to the material-saving and tool-free characteristics of AM. As a result, it is clear that while companies may not currently consider themselves to be suited to AM, it only takes a few small changes to start taking advantage of this innovative technology.

THE SWITCH TO 3D PRINTING—HOW TO GET THE MOST OUT OF THIS GAME-CHANGING TECHNOLOGY

While the implementation of AM requires relatively few changes, adopting a wholly new manufacturing process does, of course, require patience and can pose challenges in terms of mindset changes. Having an experienced partner is a key element in the optimal integration of AM into existing processes and structures. Having worked with many customers across research and industry, Lithoz understands the importance of supporting new and existing AM adopters and has therefore tailored its business model to support clients all the way from initial adoption to eventual scale-up. We offer our customers an experienced support service that enables them to seamlessly integrate our ceramic 3D printing technology and, when the time comes, implement scale-up capabilities for serial production.

In May 2020, Lithoz opened the Lithoz Innovation Lab (LIL, Fig. 6) for this precise purpose—to advance ceramic 3D printing and enable businesses to accelerate their developments and further innovate in ceramic manufacturing. Alexander Michaelis of the Fraunhofer Institute for Ceramic Technologies and Systems IKTS gave his opinion of the new space: "This new state-of-the-art facility is a huge leap forward, as it gives

Figure 5. From small, complex parts such as aerospike nozzles (above) up to much larger industrial components such as casting cores (right), AM can produce near limitless geometries. *Credit: Lithoz*

industry and R&D the opportunity to push the limits of ceramic 3D printing, while making discoveries along the way."

By ensuring that businesses are fully using AM for their industries, we are helping the growth of the AM market as an established manufacturing technology. Johannes Homa, CEO of Lithoz, says, "We see ourselves not only as a machine supplier, but as a partner for our customers. We have learned that a partnership approach is the key to successfully implement ceramic AM. AM has already made huge waves in many industries, and we at Lithoz are looking forward to seeing the new applications this technology will offer and where it will take us in the years to come."


Figure 6. The newly opened Lithoz Innovation Lab. *Credit: Lithoz*

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THE PROMISING **PATH FORWARD** FOR ADDITIVELY **MANUFACTURED** CERAMICS

By David Holthaus

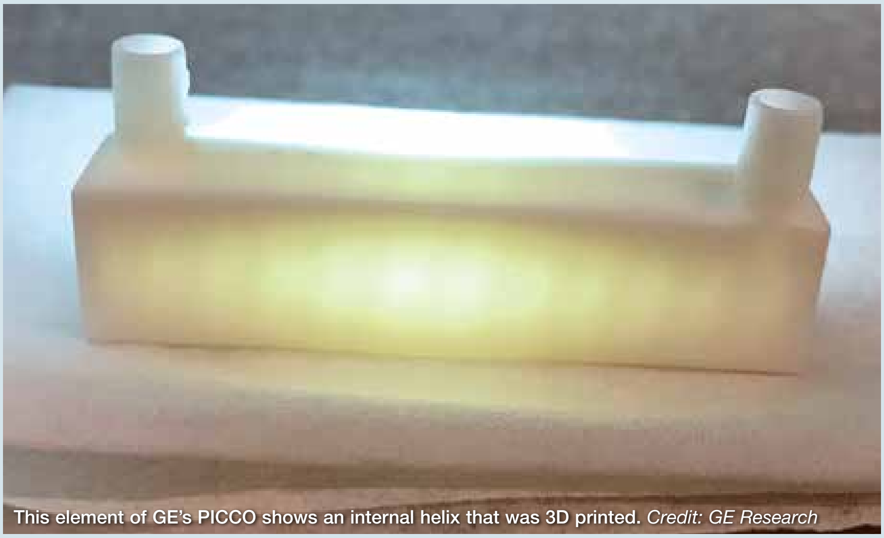
The Army's Bradley Fighting Vehicle is being us

The U.S. Army is building a growing fleet of electric vehicles that demand resiliency, as well as speed and durability.

Military vehicles, of course, must perform in high-stress situations, and the inner workings and power drive systems of an electrified fleet must withstand high voltage and temperatures. The silicon carbide semiconductor chips used in these vehicles can improve the efficiency and performance, but they can face thermal challenges when pushed to extremes.

As a potential solution, the U.S. Army Research Laboratory and GE Research are working together to develop a next-generation cooling system called the Package Integrated Cyclone Cooler (PICCO) that uses additive manufacturing to create a critical component.

In PICCO, a cold plate for electronics cooling is fabricated with an internal helix that swirls boiling fluid to increase the heat transfer coefficient and the critical heat flux, says Cathleen Hoel, a senior materials scientist at GE. The cyclone cooler is made using cutting-edge additive manufacturing, or 3D-printing technology, to produce ceramic parts that will permit the power electronics packages to stay cool and maintain their performance, even when transmitting heavy loads of power.



This element of GE's PICCO shows an internal helix that was 3D printed. *Credit: GE Research*

It is a prime example of how additive manufacturing, or AM, can be put to use in advanced systems that use ceramic materials.

"At GE, we are working closely with system and component designers and learning about areas where ceramics formed by AM can play a critical role in enabling next-generation systems," Hoel says.

Additive manufacturing of ceramics, although in its early stages, is growing rapidly and the market has significant potential, experts say.

The ceramics 3D printing market is expected to generate overall revenues of more than $3.6 billion by 2028, rapid growth from

ed to prototype hybrid electric drives to reduce costs and fuel consumption. *Credit: U.S. Army photo*

AM helps engineers with rapid prototyping and demonstrations of new designs without a big investment in new tooling, says Igor Levin, a leader in the materials structure and data group at the National Institute of Standards and Technology (NIST). By offering "tool-free" fabrication, AM allows for design flaws to be discovered early, without the investment that other methods would require, he says.

The technology also holds promise for replacing parts that may have become obsolete, says Brandon Ribic, technology director at America Makes, the Youngstown, Ohio-based additive manufacturing accelerator of the National Center for Defense Manufacturing and Machining. America Makes is one of eight Manufacturing Innovation Institutes established and managed by the U.S. Department of Defense as public-private partnerships.

$185 million in 2019, according to SmarTech Analysis, a Crozet, Va.-based market research firm.

"It has a tremendous amount of upside and development potential and hasn't even scratched the surface yet," says David A. Gottfried, deputy director of business development at the Center for Advanced Ceramic Technology at Alfred University.

The Center is developing a new $7.75 million Center for Advanced Ceramic Manufacturing (CACME) at the University, which is focused on helping industry develop and commercialize additive manufacturing of ceramics and glass.

"It's not for blue-sky research," Gottfried says. "It was done as an economic development project for companies that want to develop new materials and processes."

The biggest strength of AM for ceramic manufacturing lies in its ability to make designs that cannot be made any other way, Hoel says. "Expanding the design space of ceramics, as well as metals and polymers, allows more efficient systems and the ability to overcome limitations imposed by traditional manufacturing methods," she explains.

Cathleen Hoel

Sectors that are strong candidates for ceramic AM include aerospace, power generation, energy storage, and health care, according to Hoel.

Researchers there conducted a project called "Maturation of Advanced Manufacturing for Low-Cost Sustainment (MAMLS)," which was partly funded by the Air Force Research Laboratory. Air Force aircraft have an average lifespan of about 27 years, according to the America Makes website, meaning critical parts are often out of production because they are obsolete, cost too much to create, or are made in small quantities.

The first phase of the project showed promise for additive manufacturing. "In terms of the ability to readily get out a product that gets to the customer in a shorter period of time and with low-volume production, it does offer a cost benefit and time savings," Ribic says.

The project was able to demonstrate that AM technologies could improve the ability to rapidly replace parts and improve maintenance for legacy aircraft, as well as enable on-demand replacement of damaged or obsolete components that could not be replaced through conventional supply chains.

Scaling up the volume of additively manufactured ceramic parts is something that needs more research. "That was low volume," Ribic says. "How does that scale to thousands and tens of thousands? We have a lot to learn still."

Additive manufacturing is an emerging technology, so there are growing pains. One that is unique to the ceramics industry is the need to debind and sinter parts after printing, Hoel says. The process can lead to stress and defects in the printed part, she says.

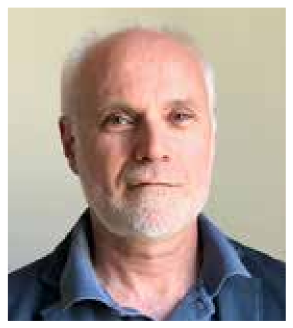
"The ceramics community has been debinding and sintering green parts for many years, so the difficulty is appreciated," she says. "AM uses binder chemistries that are not often used in traditional forming methods, so these differences need to be understood to overcome the defects."

AM can enable part designs of greater complexity, but that complexity can aggravate the challenges that are already present for printing, debinding, and sintering.

"Designs can be printed that could not be made by other methods, but the cost associated with those parts can be high because complex parts are generally more prone to defects," Hoel says.

The cyclone cooler also is an example of the challenges that can be associated with fabricating with additive. The PICCO is a complex design that can experience stress during debinding and sintering due to the nonuniform wall thicknesses in the design, Hoel says. The right ceramic slurry composition must be used to reduce those stresses.

Brandon Ribic



Igor Levin

Because AM is a nascent technology, parts made by it will be more expensive than those made by traditional methods. For that reason, GE researchers are focusing on parts that can only be made by AM and play a critical role in an advanced system, according to Hoel.

"AM is best leveraged in next-generation systems where the design benefits can be maximized and challenging aspects, such as anisotropic strength, can be managed," she says.

For example, GE is researching artificial bone scaffolds that can be used to repair damaged bone in patients. 3D printing allows for fine pore sizes to be fabricated in the artificial bone. However, removing uncured material from the pores can be challenging. "We are developing methods to effectively and consistently clean printed parts with fine pores," Hoel says.

Post-processing of additively manufactured parts is one of the main challenges for ceramic parts, Levin said. Debinding can be a source of defects, and sintering of green parts can also introduce defects and failures.

Biomedical applications are among the most promising areas for the use of additive manufacturing. The technology can enable patient-specific solutions, including for bone implants, dental implants, crowns, and bridges, as well as for medical device components and surgical tools, Levin wrote in a paper he co-authored for NIST.

"AM is envisioned to reduce the complexity of surgeries, improve biological response to implants, and lower cost" compared to conventionally manufactured materials because there is less machining, according to the paper, "Materials Research and Measurement Needs for Ceramics Additive Manufacturing," published in November 2020.[1] The paper reports on a November 2019 NIST-sponsored workshop to identify the most pressing research and metrology issues for additive manufacturing of ceramics.

The paper notes that a challenge for the health industry is to validate parts manufactured by AM. That is true for other industries using AM, Ribic says. "Inspection can be a challenge. If we're going to introduce complexity, being able to confirm that the interior features that I've put in there, that I can't see, are in the correct form and they're going to function as I anticipate them to—there needs to be a means to certify that," he says.

X-ray computed tomography has become a standard tool for certifying additively manufactured parts, but it presents challenges in ceramics because of variation in the densities of the material, Ribic says. Using acoustic sensing techniques could play a role in certifying ceramic parts, too, he adds.

Much more research is needed in this area and others, Levin says, before the technology can be more widely adopted. That is especially true for the creation of standards for feedstock materials and for identifying best practices for post-processing methods.

As the technology becomes more accessible, collaborations among industry, government agencies, and academia will help move this promising manufacturing method forward, the NIST authors say, as well as periodic meetings to review and share data.

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ALFRED UNIVERSITY-CACT PARTNERSHIP SUPPORTS LAUNCH OF START-UP COMPANY AT INCUBATORWORKS

By Mark Whitehouse and David Gottfried

ALFRED, NY—Alfred University and its Center for Advanced Ceramic Technology (CACT) are supporting the launch of a new business that will commercialize a new additive manufacturing-based system for the terra cotta industry.

William Carty, professor of ceramic engineering and the J.F. McMahon Chair in Ceramics at the Inamori School of Engineering at Alfred University, launched the new firm Replacement Tiles Solutions, which is located at the IncubatorWorks facility in Alfred. IncubatorWorks—established in 1992 and previously operated as the Ceramics Corridor Innovation Center—is a state-of-the-art incubator offering services and facilities to foster growth of entrepreneurial businesses in ceramics, glass, advanced materials, and related technology-based industries.

Replacement Tiles Solutions is developing innovative solutions to 3D scan terra cotta roof tiles and other terra cotta elements in order to produce high-resolution molds used to make precise duplicates of the material needing replacement. Because this unique process allows for near-perfect color matching, replacement terra cotta can be installed without negatively impacting a roof's aesthetics.

Replacement Tiles Solutions is working closely with Orchard Park, N.Y.-based Boston Valley Terra Cotta, a global manufacturer of architectural ceramics that will serve as a subcontractor to the new company. Alfred University alumnus John Krouse '85 (B.S., ceramic engineering) is president of Boston Valley Terra Cotta, a company with over 40 years' experience as a grade 1 terra cotta roof tile replacement company, which will assist Replacement Tiles Solutions in bringing their new process to market.

Steven Hyde, left, and Mark Ciccarella, junior ceramic engineering majors at Alfred University, observe two sample molds created in a 3D printer at Replacement Tiles Solutions, where the students work as research assistants. *Credit: IncubatorWorks/Replacement Tiles Solutions*

"Thanks to significant advances in additive manufacturing, and leveraging our decades-long experience in working with terra cotta materials, we are transforming the way terra cotta roofs are repaired," Carty says. When terra cotta roofs are damaged, it is not uncommon for the entire roof to be removed and replaced, which can be an extremely expensive proposition. "Using our process, a homeowner can not only save thousands of dollars in materials and contactor costs by replacing only the damaged tiles, but also significantly reduce the amount of time needed to conduct the repairs," Carty adds.

Replacement Tiles Solutions also partnered with CACT, one of 15 NYSTAR Centers for Advanced Technology. The CACT is providing support for internships, access to analytical services, and partnership opportunities. One such partnership includes restoration of the historic Celadon Terra Cotta building located on Alfred Village's Main Street. Built in 1892 by the Celadon Terra Cotta Company, the building was designed as a sales office and display center for the company, and was considered a "catalog" of their work. Due in large part to the Celadon Terra Cotta Company's location in Alfred, this prompted then Governor Theodore Roosevelt in 1900 to establish the New York State School of Clay-Working and Ceramics (now the New York State College of Ceramics) in Alfred.

"Thanks to funding being made available through Governor Cuomo's Smart Growth Community Grant program that was awarded to the Village of Alfred, we're able to utilize state-of-the-art technology to scan and duplicate certain terra cotta elements on that building that could otherwise never be reproduced," says John Simmins, CACT executive director.

A committee of faculty, staff, and students from Alfred University have begun the process of identifying the repairs needed to both preserve its historic elements and ensure the building is structurally secure for another hundred years.

Adds Simmins, "The CACT was launched to support the growth of New York State's ceramic industry, including the creation of start-up companies like Replacement Tiles Solutions. This is an exciting opportunity to support the growth of a new business in Alfred, leading to significant capital investment and sustainable job creation in our region."

To date, Replacement Tiles Solutions has invested approximately $500,000 in specialized equipment used in its process, and the firm employs a handful of part-time and student workers. The firm hopes to graduate from the IncubatorWorks facility within the next two years and relocate to a larger facility to allow for expanded manufacturing while remaining in the Alfred community.

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deciphering the discipline

A regular column offering the student perspective of the next generation of ceramic and glass scientists, organized by the ACerS Presidents Council of Student Advisors.

Jennifer Bullockus

Guest columnist

FIRST Robotics: An opening into the world of engineering

The field of engineering is evolving at a rapid pace in the pursuit of cutting-edge technologies. Encouraging students interested in robotics to experience the world of engineering during their secondary education will bolster the pipeline of people pursuing degrees or careers in engineering, which is important for industry.

The international nonprofit organization For Inspiration and Recognition of Science and Technology (FIRST) encourages students of all ages to become involved in robotics and technology. At the high school level, the annual FIRST Robotics Competition (FRC) gives students exposure to engineering skills through training and hours of hands-on experience designing, fabricating, and programming a robot with autonomous features. Mentors with formal education and experience in the field educate the students on the principles of engineering, prototyping, and problem solving, and teams have eight weeks to design and fabricate the robot before competitions start.

I competed in FRC when I was in middle school, and that experience led me down the path of mechanical engineering. I returned to the world of FIRST in college, when I became a mentor for the FIRST Robotics Team Citrus Circuits in Davis, California.

Since 2004, FIRST Robotics Team Citrus Circuits has won over 20 regional competitions and been a finalist at the World Championships seven years in a row. When I joined this team as a mentor, I was surprised to find their immense success stemmed from the students themselves. In other words, veteran members of the team led most of the extensive training for the new members. This situation impressed me because, within a few years of being on the team, students went from not having any previous experience to leaving the program with extensive knowledge of engineering.

Each year the competition requires that a robot perform a different series of tasks to be competitive. A typical robot can have five or more mechanisms. Common mechanisms each year include an intake system for the game piece and a shooter (projectile launcher) or pick-and-place grasp, depending on the challenge. For the 2020 competition, at the end of the match, the robot had to hang from a lever without touching the ground, so a climbing mechanism was part of the design.

As a design mentor on Citrus Circuits, we focus on training students in the computer-aided design program OnShape. Before fabrication, the entire robot is first planned and built as a 3D model on OnShape, which acts as the blueprints for robot assembly.

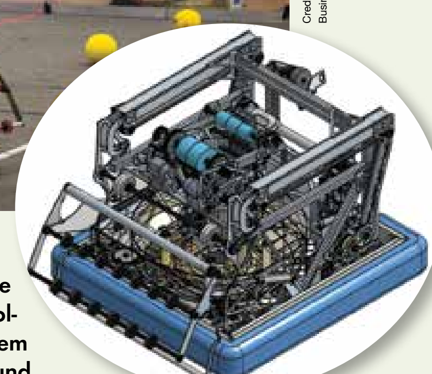
For the bulk of the frame and mechanisms, often the material of choice is aluminum for the load bearing components. Using aluminum for our bar stock and tubes, shafts, and bent sheet metal parts helps with the weight limit design restriction without compromising strength.

The other major material used on the robot is the thermoplastic polycarbonate. Polycarbonate sheets are used for parts that do not require large amounts of force because while polycarbonate has high impact strength, it is not as strong as aluminum. The polycarbonate parts are machined on a router or laser cutter, allowing for unique and precise shapes.

Each year, additively manufactured parts are used on the robot, mainly in the form of spacers and washers created using a polylactic acid filament. However, in the 2020 competition, the main sprocket of the robot's shooter mechanism was 3D printed using fused deposition modeling.

I take joy in mentoring these kids and encouraging their pursuit of engineering careers. Volunteering with Citrus Circuits as an undergraduate has greatly rounded out my knowledge of engineering as I pursue my degree. After I graduate, I want to get a job in industry working on mechanical analysis applications. However, I intend to keep volunteering with FIRST.

Jennifer Bullockus is an undergraduate student in mechanical engineering at the University of California, Davis. Between FIRST and her research for the NASA HOME project, Jennifer's research interests center around robotics. Outside of class, Jennifer drives double deck buses around Davis for Unitrans and loves jamming out on her trombone with the UC Davis Marching Band.



Credit: Jennifer Bullockus (right); Citrus Circuits Business and Media Team (above)

Computer-aided design (right) and finished model (above) of 1678 Citrus Circuit's 2020 competition robot "Emperor Pulpatine" at the LA North Regional Competition. The robot collected power cells (yellow balls) and shot them into the power port (goal) 8 feet off the ground.