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AMERICAN CERAMIC SOCIETY

bulletin

emerging ceramics & glass technology

DECEMBER 2021

Game-changers:

How ceramic and glass materials enhance performance and provide safety to sports



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Game-changers: How ceramic and glass materials enhance performance and provide safety to sports

Sports are integral to society—not only do they provide entertainment, physical activity, and leisure, but sports are deep parts of identities, cultures, and economies worldwide. The \$1.1 trillion sports market includes ripe potential for ceramic and glass materials in both established products and innovative new technologies.

by April Gocha and Lisa McDonald

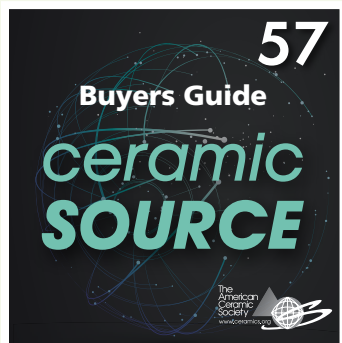


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Investigation of classical nucleation theory with novel energy landscape methods

The methods and the software developed in this work offer a promising step to gain insights into the fundamental nature of glass-ceramic nucleation and the validity of classical nucleation theory.

By Collin J. Wilkinson & John C. Mauro



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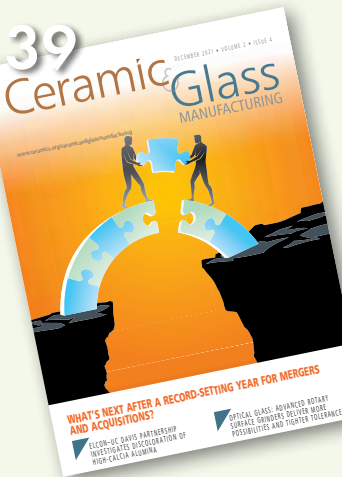
ceramicSOURCE 2022

Our annual reference and buyer's guide and directory

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What's next after a record-setting year for mergers and acquisitions?

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- Elcon-UC Davis partnership investigates discoloration of high-calcia alumina
- Optical glass: Advanced rotary surface grinders deliver more possibilities and tighter tolerances

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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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As seen on Ceramic Tech Today...



Credit: yasin hm, Unsplash

Reducing the need for trial and error—systematic selection of inorganic binders for refractories

The binder used in refractory production requires careful consideration because it can influence the refractory's final mechanical and chemical properties. Researchers in Germany advanced a selective and systematic method for choosing an inorganic binder.

Read more at www.ceramics.org/inorganicbinders

Also see our ACerS journals...

Effects of temperature and humidity on adhesion of water scale to glass substrates

By S. Hayashi, T. Kobayashi, S. Sakai, et al.
International Journal of Ceramic Engineering & Science

Densities of liquid lanthanoid sesquioxides measured with the electrostatic levitation furnace in the ISS

By C. Koyama, T. Ishikawa, H. Oda, et al.
Journal of the American Ceramic Society

A threshold heating rate for single-stage heat treatments in glass-ceramics containing seed formers

By A. Zandona, C. B. M. Groß, B. Rüdinger, and J. Deubener
Journal of the American Ceramic Society

Radial cracking at Vickers indentations in pristine flat/square silica fibers

By C. R. Kurkjian, S. M. Allameh, and S. Yoshida
International Journal of Applied Glass Science



Read more at www.ceramics.org/journals

Total knee replacement: Global markets

By BCC Publishing Staff

The global market for total knee replacement was valued at \$6.3 billion in 2020. The market is expected to grow at a compound annual growth rate of 4.1%, to reach \$8.0 billion by 2026.

Total knee replacement is a procedure whereby an artificial joint replaces a damaged knee joint. If a procedure is being performed for the first time on a patient, it is called a primary replacement procedure. Revision procedures are performed once degradation of the joint prostheses or other conditions, such as fracture, cancer, or other causes, has occurred. Generally, 90% to 95% of patients are satisfied with the outcome of their procedure. In some cases, 95% of the knee replacements remain in use after 10 to 15 years post-surgery.

Key factors driving growth in the total knee replacement market are the increasing incidence of orthopedic disorders among the population—including osteoarthritis, lower limb joint pain, and medial cartilage tear—and an aging population. Other growth factors include increasing approvals of technologically advanced products and rising R&D investments in knee replacement implants. Also, the increasing incidence of orthopedic disorders related to the growing incidence of both diabetes and obesity cases is pushing growth in the total knee replacement market.

Although the overall design of total knee implants varies, total knee implants generally have three basic components:

- **The femoral component** attaches to the end of the femur. It has a groove that provides the patellar component to

slide up and down smoothly as the knee bends and straightens.

- **The patellar component** is a dome-shaped piece that mimics the kneecap. Because the patella rests against the femur, the alignment of the patellar and femoral components is crucial for proper function.

- **The tibial component** is a flat, two-piece component attached to the tibia. It typically consists of a metal part, which lies on top of the tibia and has a stem inserted into the tibia for stability, and a plastic part, which acts as a cushion between the metal tibial component and the femoral component.

These three components are cemented in place, but some physicians use a cementless procedure that supports the bone growth into the implant to help strengthen stability.

The growing demand for tighter surgical fit has made manufacturers of total knee implants acknowledge the need for patient-centric implant designs. In response to such demands, implant manufacturers have made incremental moves to develop personalized implants. However, because customized total knee replacement surgery is a relatively new concept, there is limited data to determine if the use of custom implants offer better patient outcomes and functionality than standard knee replacement systems.

North America is estimated to have the highest market share and the Asia-Pacific region is anticipated to have the

Table 1. Global market for total knee replacement, by product category, through 2026 (\$ millions)

Product category	2019	2020	2021	2026	CAGR % (2021–2026)
Primary total knee replacement	4,514.4	4,675.3	4,825.6	5,830.0	3.9
Revision total knee replacement	1,564.3	1,635.9	1,704.9	2,160.3	4.8
Total	6,078.7	6,311.2	6,530.5	7,990.3	4.1

Table 2. Global market shares of total knee replacement, by manufacturer, 2020 (%)

Company	Market share (%)
Zimmer Biomet	33.9
Stryker	21.1
DePuy Synthes	16.7
Smith & Nephew	12.0
Others	16.3

highest growth rate during the forecast period 2021–2026. Subjects younger than 65 years of age represent the fastest-growing population of total knee replacement recipients and are anticipated to account for more than 50% of knee replacement procedures by 2030.

About the author

BCC Publishing Staff provides comprehensive analyses of global market sizing, forecasting, and industry intelligence, covering markets where advances in science and technology are improving the quality, standard, and sustainability of businesses, economies, and lives. Contact the staff at Helia.Jalili@bccresearch.com.

Resource

BCC Publishing Staff, “Total knee replacement: Global markets” BCC Research Report MDS053A, September 2021. www.bccresearch.com. ¹⁰⁰

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 2000s–present.

We hope you enjoyed 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>. ¹⁰⁰

Into the Bulletin Archives—2000s–present

Since its launch, the *Bulletin* published 12 issues every year, but that changed in the 2000s. The *Bulletin* dropped to 10 issues in 2009 (by combining June/July and October/November) and then nine issues in 2010 (by combining January/February).

Expansions to the Society structure is one of the main trends tracked by the *Bulletin* in the 2000s and 2010s. These expansions were driven by concerns in the early 2000s about declines in participation, member-

ship, and finances, so “the Board...took a more hands-on approach in addressing these issues,” according to a state of the Society report in the October 2006 issue. Some of the changes to better serve membership include

- 2005—Formation of the Material Advantage student program with ASM, AIST, and TMS. (Read more in the September 2005 issue, p. 23)
- 2008—Formation of the President’s Council of Students Advisors. (Read more in the June 2008 issue, p. 20)
- 2009—Formation of the Young Professionals Network. (Read more in the September 2009 issue, p. 43)
- 2017—Formation of ACerS International Chapters. (Read more in the September 2017 issue, p. 3)

The Society also launched the Ceramic and Glass Industry Foundation in 2014, as described in the January/February 2014 issue. The Foundation’s goal is to promote the formation of a working association between industries and universities to develop the next generation of ceramic and glass scientists and engineers.

The ACerS journals also witnessed significant expansion in the last two decades, with the launch of three new journals:

- 2004—*International Journal of Applied Ceramic Technology*, announced in the October 2003 issue.
- 2010—*International Journal of Applied Glass Science*, announced in the June/July 2009 issue.
- 2019—*International Journal of Ceramic Engineering & Science*, announced in the October/November 2018 issue.

Several changes occurred to the Society Division structure in the 2000s. The July 2000 issue reported



For three decades, The American Ceramic Society conducted the International Conference on Advanced Ceramics & Composites in Cocoa Beach, Fla. In 2007, however, the Society moved ICACC to Daytona Beach, Fla., to accommodate increased attendance and an expanded number of exhibits. Above are images from the first ICACC at Daytona Beach.

2000s

that the Materials & Equipment Division and the Whitewares Division merged to form a single Division after struggling for several years with programming needs and a decline in meeting attendance. However, because the ACerS Constitution does not have a procedure to allow Divisions to merge, each Division petitioned the Board to change its name to Whitewares & Materials and adopted the same purpose. The July issue also reported that the Design Division changed its name back to Art, the name it originally held before changing to Design in the 1940s.

The 2010s witnessed a few more changes to the Divisions, bringing us to the structure that the Society has today. The March 2013 issue reported on the renaming of the Art Division to the Art, Archaeology & Conservation Science Division, a change made to better reflect “the numerous intersection points between art and materials science.” Two years later, the May 2015 issue announced the transformation of the inactive Whitewares & Materials Division into the new Manufacturing Division, which has a much broader



William “Bill” Lee, left, receives the ceremonial ceramic gavel from Mrityunjay Singh. Lee was the first Society president who resided outside the United States during his term.

focus to meet the needs of today’s manufacturers.

The Society witnessed the creation of an entirely new Division in 2017. The January/February 2018 issue announced the launch of the Bioceramics Division, which was formed out of the ~90-member Bioceramic Technical Interest Group. The last Division to undergo a rebranding was the Nuclear & Environmental Technology Division, which became part of the new Energy Materials and Systems Division in 2020, as announced in that year’s March issue.

DIVISIONS OF THE SOCIETY

During the 2000s, the Society had 10 Divisions.

- Art (previously Design)
- Basic Science
- Cements
- Electronics
- Engineering Ceramics
- Glass & Optical Materials
- Nuclear & Environmental Technology
- Refractory Ceramics
- Structural Clay Products
- Whitewares & Materials (merger of Whitewares and Materials & Equipment)

During the 2010s, the Society had 11 Divisions.

- Art, Archaeology & Conservation Science (previously Art)
- Basic Science
- **Bioceramics (New)**
- Cements
- Electronics
- Energy Materials and Systems (previously Nuclear & Environmental Technology)
- Engineering Ceramics
- Glass & Optical Materials
- Manufacturing (previously Whitewares & Materials)
- Refractory Ceramics
- Structural Clay Products

Ceramic and glass manufacturers flex muscles at **ceramics expo 2015**



The first Ceramics Expo took place April 26–28, 2015, in Cleveland, Ohio. ACerS is the founding partner of the annual show, which is run by U.K.-based event company Smarter Shows.

SOCIETY DIVISION SECTION CHAPTER NEWS



FOR MORE
INFORMATION:

ceramics.org

Welcome new ACerS Corporate Partners

ACerS is pleased to welcome its newest Corporate Partners:



– Bekeson Glass, LLC



– Petroceramics S.P.A.

To learn about the benefits of ACerS Corporate Partnership, contact Kevin Thompson, membership director, at (614) 794-5894 or kthompson@ceramics.org. ¹⁰⁰

2021 Pittsburgh Section annual golf outing

The Annual Golf Outing of the ACerS Pittsburgh Section returned on Monday, Sept. 13, at Lenape Heights Golf Resort. Participants enjoyed a complete program of special events, including 18 holes of golf, dinner, prizes and awards, and more. Thank you to Fiven North America, Inc. for sponsoring the \$10,000 Hole in One challenge. Golfers enjoyed competing for the prize even though no one took it home. ¹⁰⁰



ACerS welcomes new Southern California Section

At ACerS Annual Meeting at MS&T21, the ACerS Board of Directors approved the establishment of the Southern California Section. The officers of the new Section are

Chair: **Toby Schaedler**, HRL Laboratories

Secretary: **Ryan McCarty**, SAFCell

Treasurer: **Ellen Heian**

Congratulations to the newest ACerS Section! ¹⁰⁰

Central Pennsylvania Section welcomes new Section chair

With the recent retirement of John Hellmann, FACerS, the Central Pennsylvania Section welcomes Allen Kimel from The Pennsylvania State University as its chair. Congratulations, John Hellmann, on your retirement, and welcome, Allen Kimel! ¹⁰⁰

Thailand Chapter plans ICAPMA-JMAG for December 2021

The Joint International Conference on Applied Physics and Materials Applications & Applied Magnetism and Ferroelectrics is Dec. 1–4, 2021. Visit the website at <https://www.matscitech-thailand.com/2021/index.php> for more information. ¹⁰⁰

Western New York Section October meeting focuses on processing



Carty

William Carty, FACerS, Emeritus Professor of Ceramic Engineering in the Kazuo Inamori School of Engineering at New York State College of Ceramics, Alfred University, spoke on Thursday, Oct. 7, 2021, at the Western New York Section meeting on the topic, *It starts with ceramic processing (Think like a particle)*. ¹⁰⁰

ACerS members in ASM's 2021 Class of Fellows



Armstrong

Beth L. Armstrong, FASM
Senior research staff
Oak Ridge National
Laboratory
Oak Ridge, Tenn.



Balani

Kantesh Balani, FASM
Professor
Indian Institute of
Technology
Kanpur, India



Du

Jincheng Du, FACerS, FASM
Professor
University of North Texas
Denton, Texas



Madsen

Lynnette D. Madsen, FACerS, FASM
Program director
National Science
Foundation
Alexandria, Va.



Shareef

Iqbal Shareef, FASM
Professor, industrial and
manufacturing
engineering
Bradley University
Peoria, Ill.



Sundaram

S.K. Sundaram, FACerS, FASM
Inamori Professor of
Materials Science and
Engineering
Kazuo Inamori School of
Engineering
The New York State College of Ceramics
Alfred University, Alfred, N.Y. ¹⁰⁰

Volunteer spotlight

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



Reaney

Ian Reaney is the Dyson Chair in Ceramics at University of Sheffield in Sheffield, United Kingdom, and the director for the £2 million Transforming Foundation Industries Network Plus. He obtained his Ph.D. from the University of Manchester, U.K., and has served as an adjunct professor at The Pennsylvania State University and University of Aveiro, Portugal.

Reaney currently serves as the chair of the ACerS United Kingdom Chapter. He previously won the ACerS Electronics Division Edward C. Henry Award. Additionally, he was awarded the Verulam Medal for Ceramics and the Robert E. Newnham Award, and is a Fellow of the Royal Microscopical Society and Institute of Mining Minerals and Materials.



Gerhardt

Rosario Gerhardt, FACerS, is senior Goizueta Faculty Chair at the Georgia Institute of Technology. Prior to Georgia Tech, she was at Rutgers University.

Gerhardt's membership with ACerS began in the 1980s as a graduate student at Columbia University. An ACerS Fellow since 2000, she was profiled in a book focused on women in ceramics and glass in 2015, received the Friedberg Lecture award in 2017, and was recently elected to the World Academy of Ceramics. She is also a Senior Member of the Institute of Electrical and Electronics Engineers.

Gerhardt is active in the Electronics Division of ACerS. In addition to serving on its executive committee, she served as chair of the Electronics Division. She also served on the ACerS *Bulletin* Advisory Board; as advisor to the Georgia Tech student chapter of ACerS; and as a judge of student posters, papers, and GEMS awardees. Most recently, she served as a member of the awards committee for the Education and Professional Development Council.

We extend our deep appreciation to Reaney and Gerhardt for their service to our Society! ¹⁰⁰

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.



Boccaccini

Aldo R. Boccaccini, FACerS, professor and head of the Institute of Biomaterials at University of Erlangen-Nuremberg, Germany, was elected vice-president of the Federation of European Materials Societies. Boccaccini has been a member of the Executive Committee of FEMS since 2016, representing the German Materials Society.



McGuffin-Cawley

Jim McGuffin-Cawley, professor of materials science and senior associate dean of the Case School of Engineering, received the Meritorious Service Award, which recognizes outstanding service to the Case Alumni Association and to Case Western Reserve University in Cleveland, Ohio.



Seal

Sudipta Seal, FACerS, FASM, MSE, AMPAC Materials Science & Engineering, University of Central Florida, was awarded the 2021 Alpha Sigma Mu Lecture, titled *Innovation through design strategy: A material's journey from coatings to biomedical intervention*.



Varshneya

Arun Varshneya, FACerS and ACerS DLM, was honored by the Case Alumni Association for his professional achievements and his support of today's students. He received the Gold Medal, the association's highest annual honor, at Case Western Reserve University's Homecoming and Reunion Weekend, Oct. 9–10, 2021. ¹⁰⁰

more SOCIETY DIVISION SECTION CHAPTER NEWS



Frontiers of Ceramics & Glass Webinar Series

DECEMBER 9, 2021
2:00 P.M. EASTERN US TIME

Title: *A Density Functional Theory (DFT) Investigation of Small Molecule Adsorption on Mineral Surfaces in Cultural Heritage*

PRESENTER:

JESSICA HEIMANN – University of Maryland Baltimore County (UMBC)

Hosted by: Art, Archaeology and Conservation Science Division

Free to ACerS members

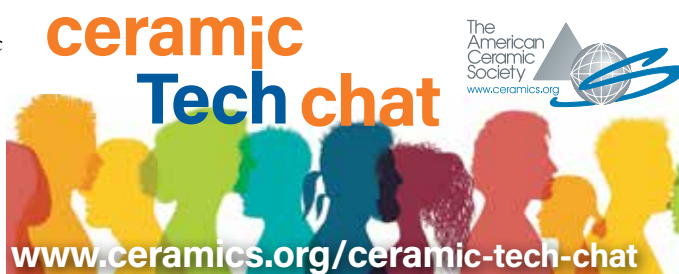
Ceramic Tech Chat: Sossina Haile and Olivia Graeve

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.

September guest,
Sossina Haile, FACerS,
Walter P. Murphy
Professor of Materials
Science and Engineering at
Northwestern University,
discusses fuel cell technol-
ogy, her experience as an
immigrant pursuing science, and tips for diversification in both of these areas.

In the October episode, Olivia Graeve, FACerS, professor of mechanical and aerospace engineering at the University of California, San Diego, discusses growing up in Tijuana, Mexico, why she believes compassion is the key to a diverse community, and describes her work building bridges between Mexico and the U.S. as director of the CaliBaja Center for Resilient Materials & Systems.

Listen to Haile and Graeve's interviews—and all of our other Ceramic Tech Chat episodes—at <http://ceramicttechchat.ceramics.org/974767>. ¹⁰⁰



IN MEMORIAM

Michael Hardwick

Akio Kato

Patrick J. Leonard

Vojislav Mitic

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

Lithoz celebrates 10 years

Lithoz GmbH (Vienna, Austria) celebrated its 10-year anniversary as a provider of 3D printing machines and materials. Initially founded as a spin-off from TU Wien in 2011, Lithoz was created to establish ceramic 3D printing as a reliable manufacturing process for industrial mass production. View a video with anniversary celebration highlights at <https://www.youtube.com/watch?v=1NxzuCSPtqE>. ¹⁰⁰


Mo-Sci Corporation and ETS Technology Holdings sold to Heraeus

The Heraeus Group (Hanau, Germany) acquired Mo-Sci Corporation and ETS Technology Holdings, LLC, both located in Rolla, Mo. Mo-Sci was founded by Delbert Day in 1985, and ETS was founded in 2012. See p. 44 for more details. ¹⁰⁰

AWARDS AND DEADLINES



ACerS runs a thriving awards program that recognizes the contributions of deserving individuals and companies within the ceramics and glass community. For more information, visit ceramics.org/awards or contact Erica Zimmerman at ezimmerman@ceramics.org.

Division	Award	Nomination Deadline	Description
AACS	Anna O. Shepard	Jan. 15, 2022	Presented to an individual(s) who has made outstanding contributions to materials science applied to art, archaeology, architecture, or cultural heritage.
BSD	Early Discovery	Jan. 15, 2022	Recognizes an early career member of ACerS who has demonstrated a contribution to basic science in the field of glass and ceramics.
Cements	Early Career	Jan. 15, 2022	Recognizes an outstanding early career scientist who is conducting research in the field of cement and concrete in academia, industry, or a government funded laboratory.
GOMD	Norbert J. Kreidl	Jan. 21, 2022	Recognizes research excellence in glass science. Open to all degree-seeking graduate students (M.S. or Ph.D.) or those who have graduated within a twelve-month period of the annual GOMD meeting.
GOMD	George W. Morey	Jan. 21, 2022	Recognizes new and original work in the field of glass science and technology. The criterion for winning the award is excellence in publication of work, either experimental or theoretical, done by an individual.
GOMD	L. David Pye Lifetime	Jan. 21, 2022	Given to deserving a individual(s) in recognition of lifetime dedication, vision, and accomplishments in advancing the fields of glass science, glass engineering, and glass art.
GOMD	Stookey Lecture	Jan. 21, 2022	Recognizes an individual's lifetime of innovative exploratory work or noteworthy contributions of outstanding research on new materials, phenomena, or processes involving glass, that have commercial significance or the potential for commercial impact.
GOMD	Varshneya-Mauro-Jain Guru-Chela Travel Fund	Jan. 21, 2022	Recognizes the special bond of knowledge, trust, and growth between a teacher ("Guru") and a student ("Chela"), benefitting both. 

FOR MORE
INFORMATION:

ceramics.org/members/awards

more AWARDS AND DEADLINES

Society and Division award nominations due mid-January

Nominations are encouraged for candidates from groups that have been underrepresented in ACerS awards relative to their participation in the Society, including women, underrepresented minorities, industry scientists and engineers, and international members. We urge you to submit nominations by **Jan. 15, 2022**, for many Society and Division awards. ¹⁰⁰

ACerS Corporate awards: January 15 deadline

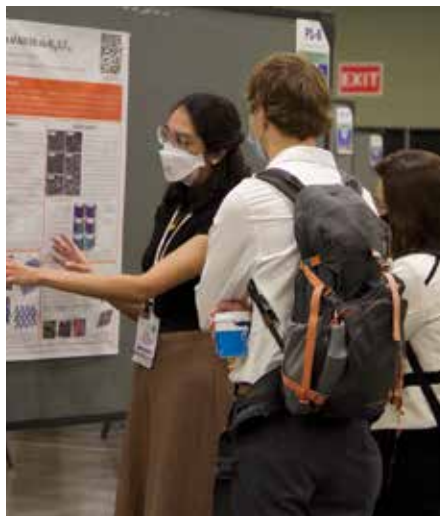
While ACerS has a large and varied awards program, there are awards specifically designed for our important group of Corporate Partners. Each award will be presented at the ACerS Annual Meeting in October 2022 in Pittsburgh, Pa. Corporate awards are a wonderful way for your organization and talented employees to be recognized for their achievements.

For more information about each award, visit ceramics.org/awards or contact Erica Zimmerman at ezimmerman@ceramics.org. ¹⁰⁰

EMSD logo contest

Are you creative? Could you use a \$500 Amazon gift card? The Energy Materials and Systems Division seeks design submissions for their Division logo! Deadline is **Jan. 5, 2022**. For more details, visit <https://bit.ly/EMSDLogoContest>. ¹⁰⁰

STUDENTS AND OUTREACH



FOR MORE
INFORMATION:

ceramics.org/students

ACerS Morgan Medal and Global Distinguished Doctoral Dissertation Award

Plan to submit a nomination for the Morgan Medal and Global Distinguished Doctoral Dissertation Award. This award recognizes a distinguished doctoral dissertation in the ceramics and glass discipline. The award is generously sponsored by Morgan Advanced Materials and includes the Morgan Medal.

Nominations should be made by a person very familiar with the student's work, such as the research supervisor. It is expected that the student will collaborate in the preparation of the nomination package.

Review nomination instructions at www.ceramics.org/doctoraldissertationaward, and submit the nomination materials by **Jan. 15, 2022**. ¹⁰⁰

BSD Ceramographic awardees

Roland B. Snow Award for Best in Show

Single crystalline galaxy
Joseph Wood and Klaus van Benthem
University of California, Davis

Transmission electron microscopy category

First place: *Nano penguin*
Boyi Qu and Klaus van Benthem
University of California, Davis

Scanning electron microscopy category

First place: *Single crystalline galaxy*
Joseph Wood and Klaus van Benthem
University of California, Davis
Second place: *A starry night*
Bo Yang, Xin Li Phuah, Haiyan Wang, and Xinghang Zhang
Purdue University

Third place: *Pollen derived carbons*
Jialing Tang and Vilas Pol
Purdue University

Scanning probe microscopy category

First place: *Hummingbird plastically imprinted*

Xufei Fang^{1,2}, Tingting Zhu¹, Kuan Ding¹, and Atsutomo Nakamura²

¹Technical University of Darmstadt, Germany

²Osaka University, Japan

Second place: *Micro domain city*
Oliver Preuss, Fangping Zhuo, Jürgen Rödel, and Xufei Fang
Technical University of Darmstadt, Germany ¹⁰⁰

more STUDENTS AND OUTREACH

MS&T21 student contest winners

The Material Advantage Student Program sponsored various contests for undergraduate and graduate students during MS&T21 in Columbus, Ohio. Thank you to all who helped judge and organize the contests this year, and congratulations to all the student winners.

Material Advantage Graduate Student Poster Competition

1st place - \$250

Celia Chari, California Institute of Technology

2nd place - \$150

Rupesh Rajendran, Georgia Institute of Technology

3rd place - \$100

Gaurav Singh, Indian Institute of Technology Madras

Material Advantage Undergraduate Student Poster

1st place - \$250

Amelia Martinez, University of Missouri Science and Technology

2nd place - \$150

Mirra Rasmussen, Case Western Reserve University

3rd place - \$100

Hugh Smith, Case Western Reserve University

Material Advantage Undergraduate Student Speaking Contest

1st place - \$500

Alison Nunes, University of Illinois, Urbana-Champaign

2nd place - \$250

Mingwei Xu, Case Western Reserve University

3rd place - \$150

Yulia Kirina, Virginia Polytechnic Institute and State University

4th place - \$100

Yuxi Zhang, Wuhan University of Technology

Material Advantage Ceramic Mug Drop Contest—Organized by Keramos

Winner - \$100 and trophy

Sophie Grier, Missouri University of Science and Technology

Most aesthetic mug - \$50

Elliot Sutalski, Missouri University of Science and Technology

VIRTUAL: Most aesthetic mug - \$50

Claire Pallett, Missouri University of Science and Technology

Material Advantage Ceramic Disc Golf Contest—Organized by Keramos

Winner - \$100 and trophy


Camden Holloway, Virginia Polytechnic Institute and State University

VIRTUAL: Most aesthetic disc - \$100

Jacob Stacy, Missouri University of Science and Technology

Material Advantage Social Media Contest

\$100

Neelam Meena, Indian Institute of Technology Bombay 

more STUDENTS AND OUTREACH

Congratulations to the 2021 GEMS awardees

The ACerS Basic Science Division recently announced the winners of its 2021 Graduate Excellence in Materials Science Awards. Congratulations to the 2021 GEMS Award Finalists.

Diamond Ranking:

- **Corey Carlos**, University of Wisconsin-Madison
- **Eeshani Paresh Godbole**, University of Minnesota
- **Spencer Dahl**, University of California, Davis

Graduate students whose abstracts are accepted for a talk at ACerS Annual Meeting at MS&T22 in Pittsburgh, Pa., should consider applying for the 2022 GEMS Awards. For more information, visit www.ceramics.org/gems. ¹⁰⁰

Grad students: Choose GGRN to advance your career

Build an international network of peers within the ceramic and glass community by joining the Global Graduate Researcher Network. GGRN is ACerS membership option that addresses the professional and career development needs of graduate level research students who have a primary interest in ceramics and glass.

Membership in GGRN is only \$30 per year. Visit www.ceramics.org/ggrn to learn how GGRN membership can help you in your future career. You may also contact Yolanda Natividad, ACerS member engagement manager, at ynatividad@ceramics.org if you have any questions. ¹⁰⁰

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

ACerS Associate Membership connects you to more than 9,000 professionals and students from more than 70 countries. 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, ACerS member engagement manager, at ynatividad@ceramics.org. ¹⁰⁰

Winter Workshop

JAN. 21–23, 2022 • DAYTONA BEACH, FL, USA

Winter Workshop 2022 will be held in conjunction with the 46th International Conference and Exposition on Advanced Ceramics and Composites (ICACC) at the Hilton Daytona Beach Oceanfront Resort, Daytona Beach, Fla. Eligible attendees are undergraduate and graduate students. Both Ph.D. students and post-doctoral researchers are eligible as well, with priority given to Ph.D. students.

Winter Workshop will begin on Friday evening with a welcome social hour, dinner, and introductory activity. Saturday morning will be filled with special presentations by noted scientists in the fields of advanced ceramics and composites. A professional development workshop will take place in the afternoon and will be followed by a social hour and dinner. A tour of Kennedy Space Center is scheduled for Sunday prior to the opening reception for ICACC on Sunday evening.

The registration fee of \$635 will cover five nights (January 21–25) at the Hilton Daytona Beach Oceanfront Resort (shared housing), Winter Workshop, Kennedy Space Center Tour, and activities of ICACC (through January 25). If you have a traveling companion who is not attending Winter Workshop, they can register for the Kennedy Space Center Tour separately.

A poster session will be held on Tuesday, Jan. 25. Contact Marilyn Stoltz at mstoltz@ceramics.org for information.

For questions about Winter Workshop, contact Amanda Engen at aengen@ceramics.org.

To register, visit <https://ceramics.org/winter-workshop-2022>.

CERAMIC AND GLASS INDUSTRY
FOUNDATION

New neural network demonstrates enhanced symmetry awareness

Researchers from Lehigh and Stanford universities developed a new machine learning algorithm that includes symmetry-aware features to improve modeling of materials.

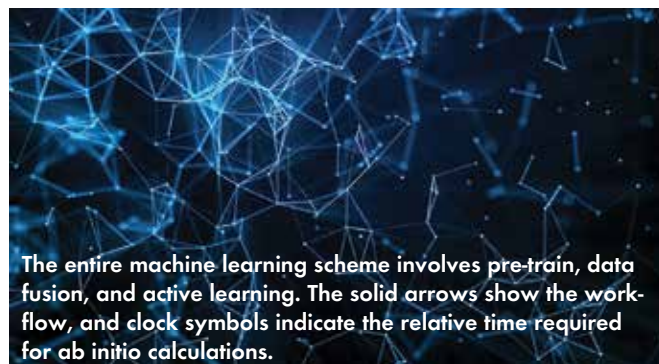
A material's structure plays a major role in determining the material's properties and behavior. Unfortunately, convolutional neural networks (CNNs), a type of machine learning commonly used to analyze visual imagery, are unable to easily detect these structural features because of their inability to recognize an image when it is rotated.

Techniques such as 2D-rotational equivariant and 3D-euclidian neural networks can correct this limitation, but the fact remains that CNNs do not inherently understand symmetry. Thus, the corrective techniques generally only allow for narrow-bounded conclusions, and if a new example lies on the periphery of the training data distribution, the predictions might be nonsensical.

Currently, it is not possible to develop a neural network that inherently understands symmetry. However, improving a neural network's ability to approximate symmetry without relying on corrective techniques is an achievable goal—and the one aimed for by the researchers of the recent study.

They began by developing and training two complementary neural network-based algorithms. One neural network can classify natural images, and the other can classify images that belong to wallpaper group symmetries, i.e., mathematical classifications of 2D repetitive patterns. After training the algorithms, they used manifold learning techniques to create 2D projections that correlated images based on their composition and structure, irrespective of the length scale of the images. Repeated exploration revealed more nuanced details of the image similarities.

After proving the potential of their network on the generated images, the researchers applied their neural network to piezoresponse force microscopy images collected on diverse materials systems over five years at the University of Califor-



Credit: Tymalov et al., *npj Computational Materials* (CC BY 4.0)

nia, Berkeley. The results? The network successfully grouped similar classes of materials together and observed trends, even though it did not have an inherent understanding of the materials system, structure, or underlying symmetry.

In an email, Lehigh assistant professor of materials science and engineering Joshua Agar says the results of this study are exciting not only because of the successful approximations but because they offer a first “use case” of an innovative new data-storage system called DataFed.

DataFed is a federated system housed at Oak Ridge National Laboratory that manages “the data storage, communication, and security infrastructure present within a network of participating organizations and facilities,” according to the ORNL website. An interdisciplinary team at Lehigh University, called the Presidential Nano-Human Interface Initiative, played an active role in the design and development of DataFed.

Agar is a part of the Presidential NHI team, and he says the new symmetry algorithm they developed will be integrated with the DataFed system to address what he sees as the two-sided problem of data science.

“There are no suitable data repositories for collecting, collating, and searching scientific data, and there are no good tools to extract knowledge simply from scientific databases. DataFed

Research News

Dancing with the light: A new way to make crystals bend by shining light

Waseda University researchers validated a new mechanism to generate fast bending motion in thick crystals using ultraviolet light. Called the “photothermal effect,” this phenomenon occurs when heat is generated by exciting materials with light. However, the bend angle dropped rapidly with increasing crystal thickness, revealing that the bending was caused by photoisomerization. Because the bending motion can now be simulated as well, it provides the basis for practical applications such as in light-driven actuators. For more information, visit <https://www.waseda.jp/top/en/news>. ¹⁰⁰

Lithium-ion batteries made with recycled materials can outlast newer counterparts

Worcester Polytechnic Institute researchers extracted the electrodes from shredded spent batteries and recovered over 90% of three key metals—nickel, manganese, and cobalt—which they used to create new cathodes. In tests of how well batteries maintain their capacity to store energy after repeated use and recharging, batteries with recycled cathodes outperformed those made with all-new commercial materials of the same composition. Specifically, it took 11,600 charging cycles for the batteries with recycled cathodes to lose 30% of their initial capacity, which is about 50% better than the 7,600 cycles for batteries with new cathodes. For more information, visit <https://www.sciencenews.org>. ¹⁰⁰

addresses the former, and the manuscript addresses the latter,” he says.

The open-access paper, published in *npj Computational Materials*, is “Symmetry-aware recursive image similarity exploration for materials microscopy” (DOI: 10.1038/s41524-021-00637-y). ¹⁰⁰

Excess aluminum extends Hall-Petch relation in nanocrystalline ceramics

Two researchers at the University of California, Davis, showed that adding extra aluminum to zinc aluminate can extend the Hall-Petch relation.

The Hall-Petch relation is a quantitative description of how yield strength of a material increases as grain size decreases. In other words, a ceramic becomes harder as its grains become smaller. However, once grains become smaller than 100 nm, researchers have observed an inverse Hall-Petch relation. Instead of the ceramic becoming harder, researchers have witnessed what they call a “softening,” i.e., its hardness begins to decrease.

Researchers for years have debated the mechanisms behind inverse Hall-Petch in ceramics. In 2019, a team led by Ricardo Castro, ACerS Fellow and professor of materials science and engineering at the University of California, Davis, suggested that cracking caused by “the activation of new energy dissipation modes” was the cause.

At that time, Castro said the next step was to define a strategy to control cracking and thereby avoid the inverse Hall-Petch relation. Now, in a paper published almost exactly two years later, Castro and graduate student Luis Sotelo Martin describe one approach to mitigate inverse Hall-Petch and extend the Hall-Petch relation.

They begin by recounting what they determined in the 2019 study—that as grain sizes decrease, the corresponding increase in grain boundary energy leads to intergranular fracture and a decrease in hardness.

“This proposed relationship between grain boundary energy (or grain bound-

ary strength) and Hall-Petch behavior suggests that the inverse Hall-Petch relation could be mitigated by avoiding an increase in grain boundary energy, suggesting ‘colossal’ hardening may be achieved in nanoceramics,” they write.

The researchers suggest off-stoichiometric compounds, or those that do not have the expected integer ratios between components, could be a way avoid an increase in grain boundary energy.

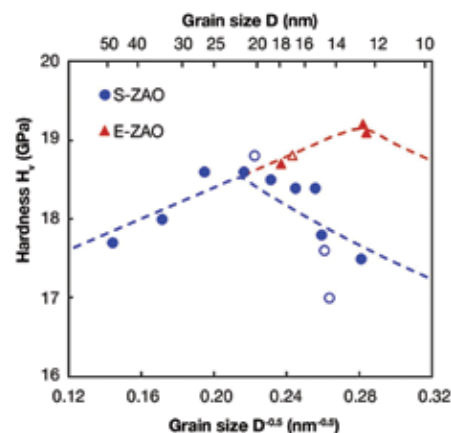
Previous studies found that ceramics featuring off-stoichiometric formulations have altered grain boundary properties. For example, studies on magnesium aluminate showed excess aluminum affected the local space charge layer and phenomena such as grain boundary migration. Also, a study on zinc aluminate showed that increasing the ratio of aluminum to zinc can suppress coarsening during sintering.

Despite its potential for altering grain boundary properties, the effect of off-stoichiometry has not been well studied in the context of the Hall-Petch relation. Castro and Sotelo Martin looked to fill that gap with their recent study, which was funded by the Army Research Office.

They used coprecipitation to synthesize a quasi-stoichiometric nanocrystalline zinc aluminate ($\text{ZnAl}_{2.01}\text{O}_4$) powder and an aluminum-rich $\text{ZnAl}_{2.87}\text{O}_4$ nanopowder. Then, they sintered the nanopowders either by deformable-punch spark plasma sintering or high-pressure spark plasma sintering.

They sintered the nanopowders in two ways to address a question arising from previous studies. Specifically, some studies that used high-pressure spark plasma sintering for fabrication reported the occurrence of inverse Hall-Petch, while some studies that fabricated their ceramics via deformable-punch spark plasma sintering did not. Because these results could indicate an effect of sintering condition on the inverse Hall-Petch relation, Castro and Sotelo Martin wanted to account for this possibility.

Following Vickers hardness testing, the researchers determined that sintering technique does not substantially affect the occurrence of inverse Hall-Petch in nanocrystalline oxides. In contrast,



Credit: Sotelo Martin and Castro, *Journal of the American Ceramic Society*

Vickers hardness plotted in Hall-Petch form for quasi-stoichiometric zinc aluminate (S-ZAO, blue) and aluminum-rich zinc aluminate (E-ZAO, red) samples along with their fits (dashed lines) according to the Sheinerman et al. model. Samples sintered using deformable-punch spark plasma sintering are denoted in hollow symbols.

excess aluminum did have an effect—while the quasi-stoichiometric samples prepared by high-pressure spark plasma sintering exhibited a maximum hardness of 18.6 GPa at a grain size of 21.4 nm, the aluminum-rich samples produced by the same technique strengthened up to 19.2 GPa at 12.6 nm grain sizes.

In the paper, Castro and Sotelo Martin explain that analysis of the samples showed aluminum enrichment altered the cracking patterns formed beneath the Vickers indentations, which affects how the samples accommodate load. Specifically, the aluminum “improves grain boundary toughness by serving as a pinning agent for grain shearing, similar to reports for rare-earth doping,” they write.

Castro adds that they have some preliminary tests showing toughness can also be improved in transparent nanoceramics with similar mechanisms. “We are expanding this concept now,” he says.

The paper, published in *Journal of the American Ceramic Society*, is “Al excess extends Hall-Petch relation in nanocrystalline zinc aluminate” (DOI: 10.1111/jace.18176). ¹⁰⁰

3D fabrication of transparent optical ceramics by lithography-based digital projection

In a recent paper, Alfred University graduate student Guangan Zhang and SUNY Empire Innovation Professor Yiquan Wu developed highly transparent yttrium aluminum garnet ($\text{Y}_3\text{Al}_5\text{O}_{12}$) ceramics via a lithography-based digital projection method.

Transparent optical ceramics are part of a special category of ceramics with unique transparent features, which lead to applications in scintillators, infrared domes, transparent windows, laser gain media, lamp envelope, phosphors, high-power LED light, optoelectronic devices, and many more.

To date, the most widely used shaping methods for transparent ceramics fabrication are powder pressing and slurry casting methods. However, to meet the industry's growing demand for customized manufacturing, scientists and researchers seek to process transparent ceramics using additive manufacturing, or 3D printing, methods.

Zhang and Wu used a CeraFab 8500 commercial 3D printer from Lithoz to perform the layer-by-layer printing process, after which they put the ceramics through pre-conditioning at 120°C, debinding at 500°C, pre-sintering at 1,000°C, and vacuum sintering at 1,750°C.

One of the challenges in the fabrication of transparent ceramics via additive manufacturing is the issue of bubbling and cracking during the debinding and sintering steps. To overcome this issue, Zhang and Wu introduced a multiple stepwise heating profile to reach the debinding temperature, followed by a single-step pre-sintering process at the appropriate tem-



Credit: Zhang and Wu

Highly transparent yttrium aluminum garnet (YAG) ceramics with 3D structures, created via a lithography printing method.

perature for $\text{Y}_4\text{Al}_2\text{O}_9$ (YAM) phase formation. The YAM serves as a “binder” to connect the Al_2O_3 and Y_2O_3 ceramic powder, which can prevent the bubbling and cracking during the final sintering process.

The fully densified ceramics were highly transparent, without distortion of the original designed geometries. Ultimately, “It is believed that additive manufacturing will enable massive fabrication of customized complex structure and scalable transparent ceramics depending on specific applications in the future,” Zhang and Wu say.

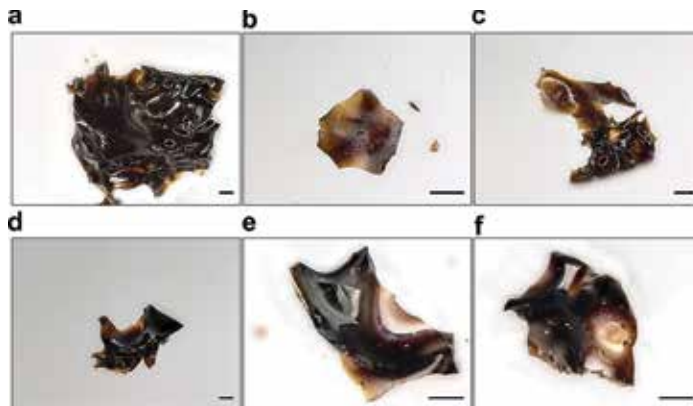
The paper, published in *Additive Manufacturing*, is “Three-dimensional printing of transparent ceramics by lithography-based digital projection” (DOI: 10.1016/j.addma.2021.102271). ¹⁰⁰

Melting the unmeltable—new method extends the range of meltable MOF materials

Researchers from the University of Jena in Germany and the University of Cambridge in the United Kingdom found a way to extend the range of meltable metal-organic framework (MOF) materials.

MOFs are highly porous crystalline compounds composed of highly ordered 3D networks of metal ions and organic ligands. MOFs are of great interest to researchers due to the material's porosity, which allows diffusion of guest molecules into the bulk structure and thus makes MOFs ideal for storage, separation, and catalysis applications.

To date, MOFs have not achieved commercial viability due to difficulties synthesizing these materials in bulk form. The relatively weak metal-ligand coordination bonds in MOFs make the materials chemically unstable, thus giving them low endurance in different types of chemical environments.



Examples of ionic liquid-incorporated ZIF-8 showing evidence of melting and glass formation after treatment in low temperature (a-c) and high temperature (d-f) conditions. Scale bars are 100 μm .

Credit: Nozari et al., Nature Communications (CC BY 4.0)

The discovery a few years ago that forming MOFs in a glassy phase gives them enough stability for bulk production was a milestone, and there are now several studies on the properties of such glasses.

Researchers have devoted particular interest to MOF glasses made from zeolitic imidazolate frameworks (ZIFs). ZIF-based MOFs exhibit higher thermal and chemical stability than other MOF subsets.

Frustratingly, only a handful of ZIFs have led to melt-quenched glasses due to the limited meltability of many ZIFs, which results from the organic ligands decomposing before the metal-ligand coordination bonds can break and reform. If the material could be modified so that the melting temperature is reached before decomposition, it would enable access to a much more diverse array of MOF glasses.


The researchers of the recent open-access paper explored the potential of ionic liquid to decrease the melting temperature. Ionic liquids are salts that exist as liquid at temperatures below 100°C. Researchers have conducted extensive experimental and computational investigations on ionic liquid–MOF composites because interaction between these materials can create new functional sites favorable for adsorption, catalysis, and ion conduction.

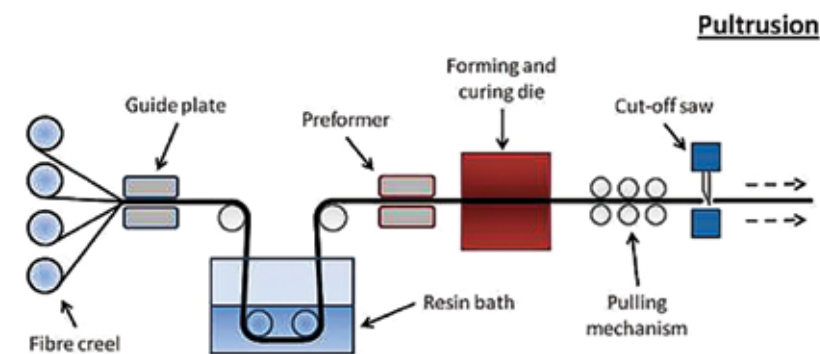
In 2017, a paper by researchers in Turkey clarified another result of the ionic liquid–MOF interaction. Specifically, they showed that the ionic liquid weakened the bond between the organic ligands and metal ions, resulting in lower thermal stability—and thus making the composite easier to melt.

For the recent study, the researchers loaded ZIF-8 with hydrophobic ionic liquid [EMIM][TFSI]. After confirming through X-ray diffraction and scanning electron microscopy that incorporating the ionic liquid did not damage the crystal structure or morphology of ZIF-8, they used thermogravimetric analyses coupled with differential scanning calorimetry to investigate what happened to the composite upon heating.

They discovered that the ionic liquid began decomposing upon heating, and the partially decomposed ionic liquid fragments helped stabilize the rapidly decomposing ZIF-8 organic ligands. This stabilization kept the material from decomposing too soon and allowed the material to reach the decreased melting temperature—and successfully undergo the process to become a glass.

“It offers exciting opportunities to melt other nonmeltable crystalline MOFs, potentially enabling a broad range of hybrid glasses with a variety of physicochemical properties and corresponding applications, in particular, ones which are derived from MOF architectures with large pore sizes,” they conclude.

The open-access paper, published in *Nature Communications*, is “Ionic liquid facilitated melting of the metal-organic framework ZIF-8” (DOI: 10.1038/s41467-021-25970-0). 



Fibres are pulled from a set of fibre reels and through a resin bath. They then pass through a preformer, which aligns the fibres into the required cross-sectional shape. The forming and curing dies finalise the shape of the composite, remove any excess resin and cure the composite so that it can be cut into sections of the necessary length by the cut-off saw. This technique is suitable for high volume, continuous production, and is able to produce parts with high fibre density and good resin dispersion.

Credit: CORE-Materials, Flickr (CC BY-NC-SA 2.0)

The potential of pultrusion to produce shape memory polymer composites

Researchers from the Skolkovo Institute of Science and Technology in Russia, plus a colleague from the University of Southern Queensland in Australia, explored the potential of pultrusion to produce shape memory polymer composites (SMPs).

SMPs are polymeric smart materials that can recover their initial shape under the influence of external stimuli, such as temperature, light, moisture, acidity, or electricity. SMPs are quickly making their mark on the materials world with applications in aerospace, biomedicine, the automotive industry, 4D printing, temperature sensors, and electronic devices.

A drawback of SMPs is their comparatively low tensile strength and stiffness, which can limit their application in demanding environments. Fortunately, researchers can improve the mechanical properties of SMPs by reinforcing the polymer matrix with various fibers, such as carbon, basalt, or glass.

Researchers have described several methods for producing SMP composites in the literature, yet surprisingly, the highly automated and continuous pultrusion process is not one of them.

In pultrusion, reinforcement fibers are impregnated with resin and then fed into a heated die where the resin is polymerized, after which the cured composite is cut to the required lengths. Not only does pultrusion offer several benefits over traditional manufacturing processes—such as high


production speed, low waste, and virtually indefinite length of the produced profiles—the final composites have a high volume fraction of reinforcement, thus ensuring excellent mechanical properties.

Based on these benefits, “it is believed that pultrusion can be successfully used to produce new types of shape memory structural components with unique combinations of geometries and mechanical properties,” the researchers write in the recent paper.

They evaluated the shape memory performance of pultruded glass fiber reinforced epoxy-based composites via a series of bending tests on flat, rectangular specimens with either 0° or 90° fiber orientation.

Test results showed that the shape programming angle had no effect on the shape fixity and shape recovery ratios. In addition, the researchers established a linear relationship between the shape fixing angle and shape programming angle, allowing them to obtain the desired shape after programming.

“Considering these results, pultruded [SMP composites] show significant promise for structural applications based on shape memory composites,” they conclude.

The paper, published in *Composites Part A: Applied Science and Manufacturing*, is “Shape memory behavior of unidirectional pultruded laminate” (DOI: 10.1016/j.compositesa.2021.106609) 



GAME-CHANGERS: How ceramic and glass materials enhance performance and provide safety to sports

By April Gocha and Lisa McDonald

Sports are integral to society—not only do they provide entertainment, physical activity, and leisure, but sports are deep parts of identities, cultures, and economies worldwide. The \$1.1 trillion sports market includes ripe potential for ceramic and glass materials in both established products and innovative new technologies.

At the Tokyo 2020 Summer Olympics, athletes set 20 new world records.¹ Yet human bodies today are not much different than they were decades ago—so how do athletes keep pushing the limits of what is physically possible?

U.S. professional tennis player Serena Williams plays in the first round of Women's Singles at the Rio 2016 Olympic Games. Williams used a Wilson Blade 104 racket, which features a braided graphite and basalt frame to improve the flex of the racket.

Credit: Andy Mash, Flickr (CC BY-NC 2.0)

Game-changers: How ceramic and glass materials enhance . . .

Part of the continual improvement of athletic performance can be attributed to our enhanced understanding of human physiology, which allows for more strategic training plans and coaching, improved nutrition to fuel athletes' bodies, and better recovery to prevent injury. Yet physiology by itself does not tell the full story. Sydney McLaughlin's sprint at Tokyo 2020, which set a new world record in the women's 400-meter hurdles at a blistering 51.46 seconds, nearly one-half second faster than the previous world record, cannot be attributed solely to tailored training and recovery plans and proper nutrition.

McLaughlin and countless other track and field athletes who competed in Tokyo can probably attribute some of their swift success to the \$1.5 million rubber track that they competed on. The track, developed by Italian company Mondo, consists of an upper layer of rubber granules engineered to provide bounce and a lower layer filled with air cavities to absorb shock, a two-part strategy that offers athletes better return of their energy. Mondo estimates that returning the energy rather than allowing it to dissipate provides athletes with as much as a 2% competitive advantage, a difference in performance that can mean setting a new world record.²

So, the question of how athletes keep pushing the limits is answered partly by technology. Advances in the materials for equipment, apparel, surfaces, and more within the sports industry have enabled bounds in performance and continue to push the limits of what the human body is athletically capable of achieving. We laud the athletes for their feats of incredible athletic performance—yet materials also play a pivotal role in enhancing and extending human performance in sports.

A big market means big potential for materials—ceramics and glass in sports

The global sports market is estimated to be worth \$1.1 trillion, according to a recent report by Signa Sports United and Boston Consulting Group.³ While that figure also includes sporting events and other sports-associated value, sports retail

including equipment and apparel holds a significant share. "Sports retail is the largest part of the sports market, accounting for \$475 billion of spending and anticipated to grow 7% annually to reach \$670

billion in 2025—at 1.4x the rate of GDP growth," the report indicates.

In other words, sports is a big, growing market with big potential for materials (Table 1).



Figure 1. A look at the many uses of ceramic and glass materials in sports.

So how do ceramic and glass materials contribute to the world of sports? While metals and polymers might be more immediately recognized in some applications, ceramics and glass are found

throughout sports as well, where the materials' desirable mechanical, electrical, and optical properties are often leveraged in combination with other materials. Though this article cannot cover

every use of ceramic and glass materials in every sport around the world, we hope to show just how integral and valuable ceramic and glass materials are throughout sports (Figure 1).

Early iterations of most sports equipment relied on natural materials such as wood, cotton, rubber, and leather. Indeed, many sports still do—professional baseballs consist of a cork or rubber core wound with yarn (mostly wool, although the outermost layer is now a cotton-polyester blend) and encased in leather, a composition largely unchanged over decades of play.⁴

But countless other types of equipment evolved sometimes drastically over the years, often leaving behind natural materials in favor of the enhanced performance offered by engineered materials. Table 2 presents a small sampling of engineered materials in sports to demonstrate the enormous breadth of applications.

Many uses of ceramics and glass in sports are realized by composite materials, which dominate in modern sports equipment. Due to their low weight and high strength, composites have infiltrated nearly every part of the sports industry, finding applications in bicycles, rackets, golf clubs, hockey sticks, fishing rods, surfboards, skis, snowboards, boats, kayaks, canoes, race cars, bobsleds, skateboards, archery bows and arrows, gymnastics bars, and even some unusual sports (see sidebar: *Obscure sports*).

Many of the composite materials used consist of a polymer matrix reinforced with fibers of ceramic or glass materials. Glass or carbon fiber-reinforced composites are most common in sports equipment, although fibers made of silicon carbide or other materials can be found as well. Sometimes, both carbon fiber and fiberglass are incorporated together. Generally, however, such equipment can be found with different varieties of fiber-reinforced composites depending on the level of competition and price range of the equipment, among other sport, region, and/or athlete preferences.

The total global market for carbon fiber reached \$4.3 billion in 2019 and is projected to be valued at \$5.5 billion in 2025. Of that entire market, sporting



Shoes

Carbon fiber inserts, plates, and other forms can be found in various footwear to protect athletes' feet and joints or to boost performance by improving energy return.

Cycling helmet

Various components of bicycles and bicycling equipment such as helmets are composed of carbon fiber and its composites. Components of wheel and brake systems for wheeled equipment such as skateboards and racing wheelchairs may be ceramic. Ceramic lubricant is used on bicycle chains.

Boxing gloves

Cleats

Spike tips on cleats can be ceramic. In addition, some sports surfaces can be concrete, covered in fiberglass, or incorporate mineral-based components.

Baseball bat

While professional baseball bats are wooden, bats for nonprofessional play can contain carbon fiber composites.

Grass

Track and field events often involved fiberglass equipment, including pole vaulting poles (which also may be carbon fiber composite) and hurdles.

Game-changers: How ceramic and glass materials enhance . . .

Table 1. Select companies involved in the sports industry*

Company (location)	Annual revenue (millions)*	Website	Role in value chain
Supply carbon fibers or carbon fiber composites			
Hexcel (Stamford, Conn.)	\$1,502	www.hexcel.com	Manufactures advanced composites, particularly carbon fiber, for diverse markets including recreation and marine.
SGL Carbon (Wiesbaden, Germany)	\$1,061	www.sglcarbon.com	Manufactures carbon and graphite materials, including fibers and composites, for diverse markets including automotive.
Teijin Carbon (Tokyo, Japan) Parent company: Teijin	— \$7,513	www.teijincarbon.com	Manufactures carbon fiber composites for diverse markets including automotive and sporting goods.
Solvay (Woodland Park, N.J.)	\$10,269	www.solvay.com	Manufactures various materials and chemicals, including composites, across diverse markets including sports and automotive.
Mitsubishi Chemical (Tokyo, Japan) Parent company: Mitsubishi Chemical Holdings	— \$29,259	www.mca-golf.com	Manufactures composite golf club shafts.
Toray Industries (Tokyo, Japan)	\$19,892	www.toray.com	Manufactures various chemicals and materials, including carbon fiber composites, for diverse markets including sports and automotive.
Supply glass fibers or glass fiber composites			
Owens Corning (Toledo, Ohio)	\$7,055	www.owenscorning.com	Manufactures insulation, roofing, and fiberglass composite materials for building and industrial applications, including boating and consumer goods.
China Jushi Co. Ltd. (Tongxiang, China)	\$1,770 [†]	www.jushi.com	Manufactures fiberglass for diverse product markets including sports and recreation, automotive, marine, electronics.
Saint-Gobain Vetrotex (Courbevoie, France) Parent company: Saint-Gobain	— \$44,025	www.vetrotextextiles.com	Manufactures fiberglass for diverse markets including marine, automotive, electronics, and sports.
Nippon Electric Glass (Otsu, Japan)	\$2,180	www.neg.co.jp/en	Manufactures glass products, including fiberglass, for diverse markets including automotive.
AGY (Aiken, S.C.)	\$221 [†]	www.agy.com	Manufactures fiberglass for diverse markets including sports, automotive, and marine.
Johns Manville (Denver, Colo.)	\$2,000 [†]	www.jm.com	Manufactures insulation, roofing, and engineered products including fiberglass and composites for diverse markets including automotive and marine.
Most valuable sports brands worldwide[†]			
Nike (Beaverton, Ore.)	\$36,800	www.nike.com	Designs, develops, manufactures, and markets sports apparel, footwear, equipment, accessories, and services.
ESPN (Bristol, Conn.)	\$13,100	www.espn.com	Sports media conglomerate that includes cable channels, broadcasting, and radio.
Adidas (Herzogenaurach, Germany)	\$11,200	www.adidas.com	Designs, manufactures, and markets sports apparel, footwear, and accessories.
Gatorade (Chicago, Ill.)	\$6,700	www.gatorade.com	Brand of sports-themed beverage and food products.
Sky Sports (London, U.K.)	\$4,400	www.skysports.com	Group of British subscription sports channels.
Puma (Herzogenaurach, Germany)	\$4,000	www.puma.com	Designs, manufactures, and markets athletic apparel, footwear, and accessories.
Under Armour (Baltimore, Md.)	\$3,500	www.underarmour.com	Designs, manufactures, and markets sports apparel and footwear.
Ultimate Fighting Championship (UFC) (Las Vegas, Nev.)	\$2,400	www.ufc.com	Mixed martial arts promotion company.
Yankee Entertainment and Sports (YES) Network (Stamford, Conn.)	\$1,500	www.yesnetwork.com	Regional sports television network primarily serving the northeast U.S.
Reebok (Boston, Mass.)	\$800	www.reebok.com	Designs, manufactures, and markets athletic apparel and footwear.

*Conversions per Google as of October 6, 2021. All financial data obtained from company reports unless otherwise noted.

[†]Private company or data not available; revenue estimated from dnb.com or google.com.

[†]Statista data from 2019 (<https://www.statista.com/statistics/253349/brand-value-of-sports-businesses-worldwide>).

goods accounted for 15.7% of the carbon fiber market in 2019, representing nearly 16 tons of the material's annual use (Figure 2).⁵ Carbon fiber composites are 40% lighter than aluminum, and thus offer significant weight savings in addition to high strength and stiffness and resistance to chemicals, corrosion, and fatigue.

Golf clubs account for the largest segment of sports uses of carbon fiber. Similar to most other types of modern sports equipment, golf clubs are multi-material—various parts of the same piece of equipment may contain several materials, and different makes and models of the equipment may incorporate a range of materials as well.

For example, the shafts of golf clubs are often made of carbon or boron fiber-reinforced composites but also may be steel, aluminum, or “titanium carbon” (a titanium alloy and carbon composite). Club heads for drivers are usually made of carbon-based composites, metals, or woods (sometimes filled with polymer foam), while heads of irons, wedges, and putters are generally composed of metals such as steel, titanium, or tungsten. Face inserts on golf club heads (a separate piece of material positioned where the club comes into contact with the ball) may be zirconia ceramic or titanium metal matrix ceramic composite.⁶

For decades, Formula One vehicles have incorporated a substantial amount of carbon fiber to reduce weight, thanks to the sport's willingness to invest in composites despite its early expensive price. Modern F1 vehicles are composed of 80% by volume composite materials, most of which are carbon fiber.⁷ As the price of carbon fiber decreases, motorsports in general continue to incorporate more carbon fiber composites to increase efficiency, in addition to the material's ability to enhance safety and handling through its high strength and stiffness.

Another place carbon fiber can be found, perhaps surprisingly, is on athletes' feet. (Table 2). A company called Carbitex (Kennewick, Wash.) developed an asymmetrically flexible carbon fiber/thermoplastic composite material that is flexible in one direction yet rigid in another, mimicking and protecting the



Figure 2. Global market for carbon fiber used in sports equipment, 2019–2025. The market is expected to grow at a compound annual growth rate of 5.7% during this time.⁵

OBSCURE SPORTS

Around the world, athletes engage in more than 200 sports recognized by national or international federations,^a yet estimates suggest there are actually more than 8,000 indigenous sports or sporting games around the world.^b No matter how you tally the count or what you consider a “sport,” it is clear that humans find a lot of ways to play and compete.

While some of the more popular sports worldwide include soccer, football, baseball, auto racing, basketball, hockey, tennis, and golf, there are diverse ways that athletes engage. The following is a sample of some more obscure sports with which you may not be familiar.^{c–e}

- **Lawnmower racing**—Competitors race modified lawnmowers around a track.
- **Underwater hockey**—also called octopush, players wear snorkels and play a form of hockey on the floor of a pool.
- **Bossaball**—Somewhat akin to volleyball, except that the game is played on a giant inflatable and involves a player on a trampoline designated as the “attacker.”
- **Zorbing**—Racing downhill in large inflatable plastic balls, akin to a hamster ball.

- **Cheese rolling**—Racing down a hill on foot to try to catch a rolling ball of cheese, which can reach speeds of about 70 mph.
- **Bog snorkeling**—Racing through a 55-meter peat bog using a snorkel and flippers.
- **Chess boxing**—A hybrid of chess and boxing, with players alternating between the two.
- **Kabaddi**—A combination of wrestling, tag, and holding players' breath, originating from South Asia.
- **Cycleball**—A combination of bicycling, soccer, hockey, and basketball, in which players hit a ball using their bicycle wheels.
- **Extreme ironing**—Ironing clothes in extreme places such as while skydiving, on a glacier, or on the roof of a speeding car.
- **Face slapping**—Competitors take turns slapping one another until someone taps out or is knocked out. 100

^aTopend Sports, “Complete list of sports from around the world,” <https://www.topendsports.com/sport/list/index.htm>

^b“How many sports are there in the world?” In *World Encyclopedia of Sports* (ISBN: 9780760316825). Archived copy available at: <https://web.archive.org/web/20100723160638/http://www.sportencyclopedia.com/index.php?mod=book>

^cK. Baumer, “The 18 strangest ‘sports’ in the world,” March 3, 2011, *Business Insider*. <https://www.businessinsider.com/obscure-weird-sports-2010-11>

^dE. Ortiz, “Strangest sports in the world,” June 4, 2021, *Stadium Talk*. <https://www.stadiumtalk.com/s/worlds-strangest-sports-a8bef81c8b8941b3>

^eD. Gachman, “Meet the fearless women of the Lone Star Mower Racing Association,” September 22, 2021, *Texas Monthly*. <https://www.texasmonthly.com/arts-entertainment/meet-fearless-women-texas-lone-star-mower-racing-association>

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motion of human joints.⁸ In another footwear application, Nike's Vaporfly 4% running shoes incorporate a curved carbon fiber plate in the shoe's midsole designed to maximize energy return in a runner's foot. That energy return amounts to an average 4% improvement in the energy a runner needs to exert to run a certain pace, called running economy.⁹

Carbon fiber, too, is finding its way into protective equipment applications. For example, professional baseball uses aerospace-grade carbon fiber compos-

ite helmets that are 300% stiffer and 130 times stronger than previous ABS plastic helmets. While those previous helmets could protect players from ball strikes up to 68 mph, the new helmets provide protection up to 100 mph.¹⁰ As carbon fiber's price continues to decrease, the material is expected to find more applications in protective sports equipment.

Besides carbon fiber, Table 2 points to other carbon-based materials that find use in sports equipment for their high strength and low weight, including

carbon nanotubes, carbon nanoparticles, and fullerenes, especially for applications to increase gliding, resist abrasion, and repel moisture.

Glass fiber-reinforced composites are another predominant composite in sports equipment. They similarly offer high strength and low weight yet at a lower cost than carbon fiber composites. Fiberglass composites can be found in many of the same sports equipment as carbon fiber composites, but they are often used in lower-cost versions, such as equipment marketed to amateurs and beginners. Composites reinforced with glass fibers are preferable to carbon fibers in some applications that do not require high stiffness.

Protective sports equipment is an important use of fiberglass composites. The U.S. market for protective sports equipment reached \$1.9 billion in 2016 and is expected to reach a value of \$2.2 billion by 2022.¹⁰ While the market is dominated by polymers due to their light weight and impact resistance, fiberglass can be found in the outer shells of many helmets and goalie/catcher masks. In addition to composites, other form factors of glass are sprinkled throughout sports for basketball backboards, safety barriers, reflective clothing, and more (Table 2).

Motorsports vehicles incorporate many sensors, electronics, and other components that use ceramic and glass materials. The rising popularity of racing series for electric vehicles, such as Formula E, offer additional opportunities for ceramic and glass materials in the vehicles' batteries as well.

Increasingly, athletes use wearable devices and electronics to track, time, and monitor athletic performance. These devices rely on ceramic and glass materials in diverse ways for the sensors, electronic components, and batteries. Further, ceramic components are found in LED lights that enable viewing of sports events and provide visibility and safety to athletes in the dark.

Other applications of ceramics include equipment that requires wear and corrosion resistance, which is especially useful for various wheel-based components that provide athletes with

Table 2. Sampling of ceramic and glass materials used in sports equipment

Carbon fiber composites	
Bicycles	Frames, forks, saddles, handlebars, wheels
Implements	Tennis rackets, hockey sticks, pole vaulting poles, ski poles, golf clubs, fishing rods
Skeleton sleds	Base plates
Racing sailboats	Up to 2,000 lbs in a 50-foot racer
Formula One cars	80% composite by volume (mostly carbon) Body components: spoilers, fenders, engine hoods, doors, roof Structural components: rear seats, roof frames, struts, door sills, pillar reinforcements System components: powertrain, motor block, brake system
Footwear	Snowboarding, cycling, watersports, running shoes, hiking boots
Protective equipment	Helmets, goalie and catcher masks
Carbon nanotube, nanoparticles, fullerenes	
Sliding sports	Ski wax, kayak coatings, ice skate blade coatings
Fiberglass composites	
Protective equipment	Helmets, goalie and catcher masks
Implements	Tennis rackets, hockey sticks, pole vaulting poles
Winter sports	Skis, snowboards, bobsleds, luge sleds
Water sports	Surfboards, paddleboards, canoes, kayaks
Field sports	Hurdles, goals and goalposts
Bulk glass	
Backboards	Tempered glass basketball backboards
Safety barriers	Hockey rinks, racquetball and squash courts, underwater aquatic viewing windows
Safety apparel	Reflective glass apparel
Electronic materials	
Auto racing	Sensors, Formula E electric vehicle racing batteries
Wearable devices	Sensors, batteries
Lighting	LED venue and athlete safety lighting
Ceramics	
Wheeled equipment (Bicycles, skateboards, wheelchairs)	Ceramic bearings, brackets, brakes, boron nitride lubricants
Shoes	Cleat tips
Skiing	Inrun ski jump tracks
Playing venues	Concrete courts, ceramic tile swimming pools, tiled aquatic arenas

SPORTS EQUIPMENT AT THE PARALYMPICS

While many eyes tuned in for the Tokyo 2020 Summer Olympics that took place in July 2021, another major international sports competition took place at the end of August—the Tokyo 2020 Paralympic Games.

The Paralympics are a series of international contests for athletes with disabilities that are associated with and held following the summer and winter Olympic Games. Developing from a 1948 sports competition for British World War II veterans with spinal cord injuries, the Paralympics has grown to welcome more than 4,500 athletes in 2021 to compete in 539 events across 22 sports. Below is a look at some of the equipment used in the Paralympics that contain ceramic and glass materials.

Running blades

Running blades are prosthetic lower limbs used by amputee runners. American medical engineer Van Phillips developed the first running blade, called the “Flex-Foot,” in the 1970s after losing part of his left leg in a motorboat accident. Unlike previous prosthetics that tried to mimic human bones, he focused on replicating ligaments and tendons. He observed animals like kangaroos and cheetahs as well as the mechanics of diving boards and pole vaulting to develop the blade design.^a

Carbon fiber is the material of choice for running blades, from the very first Flex-Foot to today. Between 30–90 sheets of carbon fiber are fused together to form the blade. Running spikes are typically fitted to the blade to help with gripping to the track.

Engineers continue to explore improvements in running blade design. For example, in 2013, Paralympian runner Blake Leeper challenged attendees at the Industrial Designers Society of

America to advance the technology of running blades. Two companies, Altair (known for product design and development) and Eastman (a chemicals and plastics manufacturing supplier) consulted with Leeper and together developed a new “F1” concept for running blades that differs from traditional blades in the following ways.^b

- **The spike plate.** Running blades are normally flat planes, but the F1 concept features a curvature that acts like an ankle, providing increased speed and efficiency on corners.
 - **Blade shape.** The F1 concept modifies the blade shape to direct more power forward instead of into the ground, improving aerodynamics.
 - **Blade attachment.** To keep the blade from falling off, the F1 concept uses both a fabric shroud and latch to lock the socket into place.
- Icelandic prosthetics firm Össur hf. is a main player in the running blade industry. They acquired the original Flex-Foot line of blades from Phillips in 2000,^c but what they are most well-known for is the Cheetah line of blades, which features blades not only designed for short- and long-distance running but also for long jumps.^d

Sports wheelchairs

Just like prosthetic limbs, sports wheelchairs must become one with the athlete’s body, otherwise performance is negatively affected. Some considerations when designing sports wheelchairs include^e

- **The seating system.** A snug and well-fitted seat ensures the shoulder joints are in a neutral safe position.
- **The seat dump,** i.e., the angle of the seat with respect to horizontal. A larger seat dump increases pelvic stability by holding the pelvis against the backrest and improves balance

by reducing the angle between the thighs and the trunk.

- **The backrest.** Backrest height should be set as low as possible to provide support to the lower back and allow the upper torso to move freely.

Wheelchairs for different sports require different designs.^f For example, fencing wheelchairs are equipped with leg straps and sturdy handles to help the athlete stay solidly seated while striking and dodging. Racing wheelchairs are designed for high speeds, so they often feature a third wheel in the front to enable a low, elongated shape, and smooth disks instead of spoked wheels to generate less air turbulence. For sports requiring maneuverability, such as basketball, the wheels are slanted to allow for faster and tighter turns. Ceramic materials used in wheelchairs include

- **Carbon fiber.** Modern advancements have increased the use of carbon fiber in sports wheelchairs. For example, carbon fiber wheels and frames are used in racing chairs such as the Top End Eliminator NRG,^g and custom molded carbon fiber seats are found in basketball chairs such as the RGK Elite CX.^h
- **Ceramic bearings.** Well-made ceramic bearings roll faster than equivalent steel bearings, thereby allowing an athlete to save their energy and achieve faster cruising speeds. AITA Ceramic—Australia International Ceramic, a Melbourne-based bearing business, worked with Australian Paralympic athlete Sam McIntosh to develop hybrid ceramic bearings specifically for wheelchair sports.ⁱ Draft Wheelchairs Ltd., a Godmanchester, U.K.-based company that provides equipment to people with disabilities, endorsed the ceramic bearings produced by Ceramic-Speed, a small specialist Danish manufacturing company, for use in racing wheelchairs.^j 100



Wheelchairs feature different designs depending on the sport for which it will be used. Left, the gold medal game in men’s wheelchair basketball at the Beijing 2008 Summer Paralympics. Right, wheelchair fencing at the London 2012 Summer Paralympics.

^a“Running blades and their evolution,” *National Paralympic Heritage Trust*, n.d. <https://www.paralympicheritage.org.uk/running-blades-and-their-evolution>

^bA. Schwartz, “These reinvented running blades could let more Paralympians into the Olympics,” *Fast Company*, 14 Aug. 2014. <https://www.fastcompany.com/3034308/these-reinvented-running-blades-could-let-more-paralympians-into-the-olympics>

^c“50 years of memorable moments, 1971–2021,” *Össur*, n.d. <https://www.ossur.com/global/about-ossur/our-company/milestones>

^d“All products,” *Össur*, <https://www.ossur.com/en-us/prosthetics/products>

^e“Wheelchair sports technology and biomechanics,” *Musculoskeletal Key*, n.d. <https://musculoskeletalkey.com/wheelchair-sports-technology-and-biomechanics>

^fS. Bushwick, “How Paralympic wheelchairs and prostheses are optimized for speed and performance,” *Scientific American*, 31 Aug. 2021. <https://www.scientificamerican.com/article/how-paralympic-wheelchairs-and-prostheses-are-optimized-for-speed-and-performance>

^gTop End Eliminator NRG, <https://topendwheelchair.invacare.com/eliminatorNRG>

^hRGK Elite CX, <https://rgkwheelchairs.com/wheelchairs/sport-wheelchairs/elite-cx.html>

ⁱ“Wheelchair bearing,” *AITA Ceramic—Australia International Ceramic*. <https://aitaceramic.com/wheelchair-bearing>

^j“Ceramic bearings for racing wheelchairs and handcycles?” *Draft Wheelchairs*, <http://www.draftwheelchairs.com/ceramic-bearings-racing-wheelchairs-handcycles>

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motion (summarized in Table 2 and the sidebar: *Paralympics*). Other examples of ceramics are found sporadically throughout sports. For instance, clay pigeons or clay traps, while not made of clay, are manufactured from petroleum pitch and calcium carbonate, and the inner weighted core of bowling balls contains a mixture of minerals embedded in a polymer resin. Readers will know of many similar applications.

In addition to sports equipment, ceramic and glass materials can be found in sports apparel (see sidebar: *A softer side*) as well as some athletic surfaces.¹¹

Game-changer: Materials innovations shift sports

Materials often enable technologies for athletic performance—so it is no surprise that as the materials used in sports evolve, so too does athletic competition.

“If you would have watched tennis 20 years ago on the professional level, you would have seen a much slower paced game,” says Jeff Bardsley, vice president of marketing for racket sports in North America at Head, a global manufacturer and provider of various sports equipment and apparel. “The ball would have been moving a lot slower, and therefore demands on the actual player wouldn’t be as high as they are today. Today’s game is very, very fast.”

That evolution can be traced back to the equipment. By reducing the weight of tennis racket frames while simultaneously increasing their stiffness, modern composite tennis rackets can be swung faster and generate more power than early wooden tennis rackets. Modern composite rackets are 22.4% lighter on average than wooden versions,¹² resulting in 17.5% faster serve speeds overall since the game’s inception in the 1870s.¹³ “Rackets now offer more power, more spin, and that’s been changing the game up just in terms of how the game is played,” Bardsley says.

Modern tennis racket frames are made of various lightweight materials, depending on the level of competition and the price point. For instance, Head manufactures lower-price rackets intended for beginners made from aluminum nylon frames. The company

also manufactures mid-level rackets from graphite composites, a combination of aluminum and graphite fiberglass or graphite composite. For its higher-level rackets, Head uses graphite, which is more expensive due to higher material cost and its more complex construction. There are variations of these types of materials in each category, but most of Head’s tennis rackets consist of carbon-based and fiberglass materials.

Despite this slight variability in materials, tennis rackets have not changed much in the past several decades, partially based on parameters set by the ruling body, the International Tennis Federation, that restrict variability in tennis rackets. “Looking at a tennis racket, there’s really only so much that you can do because it has to have a head, it has to have some form of throat, and it has to have a handle,” Bardsley says. Manufacturers can adjust some external parameters of a tennis racket frame, such as the racket length and head size, but they are relatively limited in terms of completely redesigning a racket that can be used in competition play.

That does not mean all tennis rackets are the same, however—and some of these small changes can have a significant impact on the resulting equipment. For instance, adjusting how a tennis racket is balanced from the head to the handle impacts performance. Perhaps even more adjustments can come from internal changes to the racket frame. Part of these adjustments come from changing the materials, but also changing the orientation of the materials’ fibers in one part of the frame or another, Bardsley says.

“We can also change by placing materials at different areas on the actual head of the racket to determine how the racket is going to play. The size of the sweet spot is going to be determined by the placement of the materials, the layup on the materials. By taking a similar tennis racket construction and changing the layup, changing the actual balance point of the racket, changing minor configurations, you can take two different rackets that look exactly the same and they will play completely different,” he says.

Overall, though, these variations result in relatively minor tweaks to ten-

nis rackets. Manufacturers generally are not drastically altering the design or researching entirely new materials to incorporate into the frame. They are altering the fiber orientation, slightly adjusting the frame dimensions, or testing the effect of adjusting a material in certain areas of the racket, for example.

Yet that is not to say that Head does not innovate with new materials in tennis rackets. In the early 2000s, Head introduced a new line of tennis rackets, the Intelligence collection, that incorporated piezoelectric fibers in the frame. “Our concept with the piezoelectric fibers was transforming mechanical energy into electrical energy, causing a faster snap back, giving us an opportunity to stiffen up the throat section of the racket,” Bardsley says. Those lead zirconate titanate fibers, supplied by Advanced Cerametrics Inc. (Lambertville, N.J.), generated an electrical current when the racket deformed upon contacting a tennis ball.¹⁴ A chip located in the racket’s handle amplified the signal, stiffening the frame to generate more power and reduce vibrations.

The Intelligence rackets, despite an expensive price of about \$400 almost 20 years ago, sold much better than Head anticipated. Yet Head discontinued the high-end line after being on the market for less than a decade. “We didn’t necessarily abandon it. It was more just moving on in terms of technology goes,” Bardsley says.

Today, Head’s primary focus for new technology in its tennis rackets is on graphene. The 2D carbon material provides the ability to further decrease the weight of a racket by using less material, without sacrificing stiffness or strength. While Head initially used graphene in only key limited areas of the racket—focusing on the throat section, which is a high point of distortion on the racket—it is now incorporating graphene all along the racket head and throat with its Graphene 360+ technology. “So that gives us the opportunity to really play different, and it gives a consistent and solid feel for the racket where we’ve got a consistent flexpoint, which allows more of a consistent hit or performance when the ball actually is coming off the racket,” Bardsley says.

A SOFTER SIDE: CERAMIC AND GLASS MATERIALS OFFER FUNCTIONALITY TO SPORTS FABRICS

Athletic apparel is a significant segment of the sports industry. In 2020, total global revenue for sports apparel exceeded \$188 billion, with expectations of reaching nearly \$208 billion by 2025.^a

While synthetic fabrics that provide stretch, breathability, odor control, and moisture-wicking capabilities dominate sports apparel, this segment of the sports market is not entirely devoid of ceramic and glass materials.

Apparel designed to make athletes visible in low-light conditions, such as runners jogging at night, use retroreflectivity to maximize the light reflected back to its source, such as a vehicle's headlights. This reflection is via microscopic yet precise glass beads, which reflect light directly back rather than scattering it. Often applied as a film on top of another fabric, retroreflective materials are found on a wide variety of shoes, jackets, apparel, and accessories.

In 2017, 3M released a new retroreflective material, Carbon Black, that appears black in daylight, as opposed to the silver color of most retroreflective materials. The company achieved the black color through a proprietary process that "makes the color inherent to the material's construction," according to a 3M press release.^b



3M's Carbon Black technology appears black in daylight yet contains small glass beads that are highly retroreflective. Most retroreflective materials appear as a silver color.

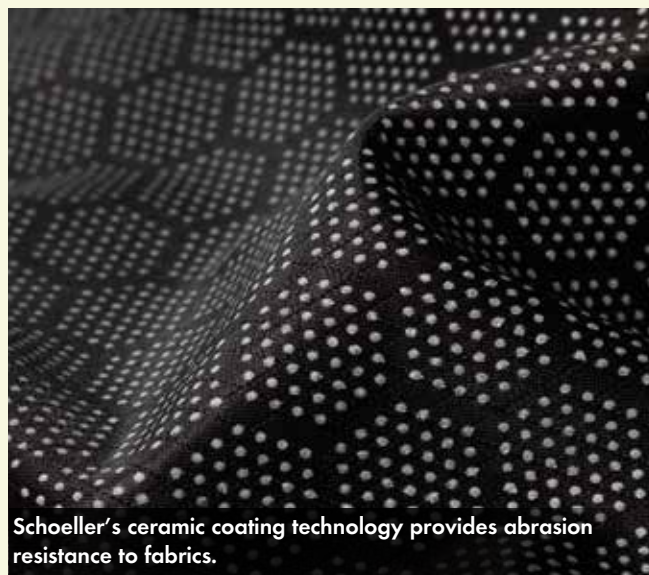
Credit: 3M

In addition to visibility, ceramic materials can be found on sports apparel fabrics designed to provide abrasion and wear resistance.

For example, Swiss company Schoeller manufactures a durable and abrasion-resistant textile with a ceramic coating for applications such as cycling. "The ceramic finishes fit together with the selected raw materials and the textile design to offer not only abrasion resistant materials with ceramic coatings, but also fall protective materials in the motorcycle or bike category," the company says.

One version of the ceramic-coated fabric, called ceraspace, is Schoeller's "particularly high-performance" fabric for applications that require maximum protection such as motorcycling. The company puts its materials through rigorous performance tests, including standardized tear and tensile strength, abrasion, elongation, pilling, weight, deformation, and weather tests, in addition to the company's own unique testing methods. According to its testing, Schoeller says ceraspace provides around three-times the abrasion resistance of high-quality leather.^c

While the composition of the ceramic is proprietary, Schoeller says the coating can be applied as either a finishing or printing process, with the ceramic applied in various designs such as small dots. The durable coatings stay on the fabric even after washing. As the company says, "they are developed to last the lifetime of the garment." ¹⁰⁰



Schoeller's ceramic coating technology provides abrasion resistance to fabrics.

Credit: Schoeller

^aStatista, 2021. <https://www.statista.com/statistics/254489/total-revenue-of-the-global-sports-apparel-market>

^b3M, "3M reinvents reflective material for activewear with Carbon Black technology," 2017. <https://news.3m.com/2017-05-02-3M-Reinvents-Reflective-Material-for-Activewear-with-Carbon-Black-Technology>

^c Schoeller. <https://www.schoeller-textiles.com/en/technologies/ceraspace>

Head's approach is reflective of that of other major companies manufacturing sports equipment in more mature product markets, in which they offer equipment manufactured with various materials for different levels of athletes. They innovate with materials and design to sell more pieces of equipment, often incrementally pushing those markets in

one direction or another. But are there opportunities for bigger innovations in the sports world?

A testbed for materials innovation

"Sports is actually a great market to test your materials. You can show off your material, you can market your material, you can test your material

in the very extreme conditions," says Erik Khranovskyy, CEO of Grafren AB (Linköping, Sweden). Grafren specializes in graphene-coated textiles, which provide the ability to incorporate sensing and power functions within clothing, including athletic apparel (Figure 3).

Many sports markets are well-funded, willing to take chances to gain a com-

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petitive advantage, and offer a relatively lower-risk testing environment compared to medical or aeronautical markets, for example.

In addition, while regulatory bodies set guidelines or standards for use of technology in sports competitions, those rulings often are reactions to new developments rather than in anticipation of potential innovations. For instance, Speedo's LZR Racer swimsuit, which debuted at the Beijing 2008 Summer Olympics, featured a lining with thin yet stiff polyurethane panels that reduced skin friction drag by 24% compared to the company's previous racing suit fabric.¹⁵ The swimsuit improved swimmers' performance and speed so much that 98% of swimming medals won at the 2008 Olympics were by swimmers wearing the LZR Racer. The suit was so fast that some claimed it amounted to "technological doping," and by 2010 the LZR Racer and similar types of suits were banned by the international body that regulates competition in water sports.

Yet unless regulations ban or exclude certain technologies—and there often is not a precedent to do so until that technology debuts on the market—the world of sports is usually wide open to innovation, creating a ripe environment for new materials.

For example, Grafren's nano-engineering process wraps graphene flakes

precisely around individual fibers of a textile, allowing control of the graphene layer's thickness. Because every fiber is coated with a thin layer of graphene, the overall weight and porosity of the textile changes very little, making it ideal for sports apparel that needs to be breathable.

The first step of Grafren's three-step process is infiltrating graphene into the fiber. "We learned how to put the flakes inside, in the depth of the fiber," Khranovskyy says. "The second step in the process was how to fix the flakes on every single fiber, so that they lay down on the fiber."

Grafren's technique causes the graphene flakes to wrap around the textile fiber, bonding individually to the fibers. "It involves both physical forces, weak van der Waals forces, but also depending on the material, much stronger chemical bonds as well," Khranovskyy says.

The final step builds up the depth of graphene flakes on the fibers. "That's what I called graphene *mâché*, in analogy to papier *mâché*. Every flake coming in surrounds the fiber more and more, so you actually have a core-shell structure around the fiber." The graphene flakes overlap one another, creating a dense yet thin coating on individual fibers.

Grafren's water-based process does not use any binders, resulting in

homogeneous, precise, and durable graphene coating of individual textile fibers. And the process can be applied to natural fibers like cotton, synthetic fibers like polyamide, and even glass and carbon fibers.

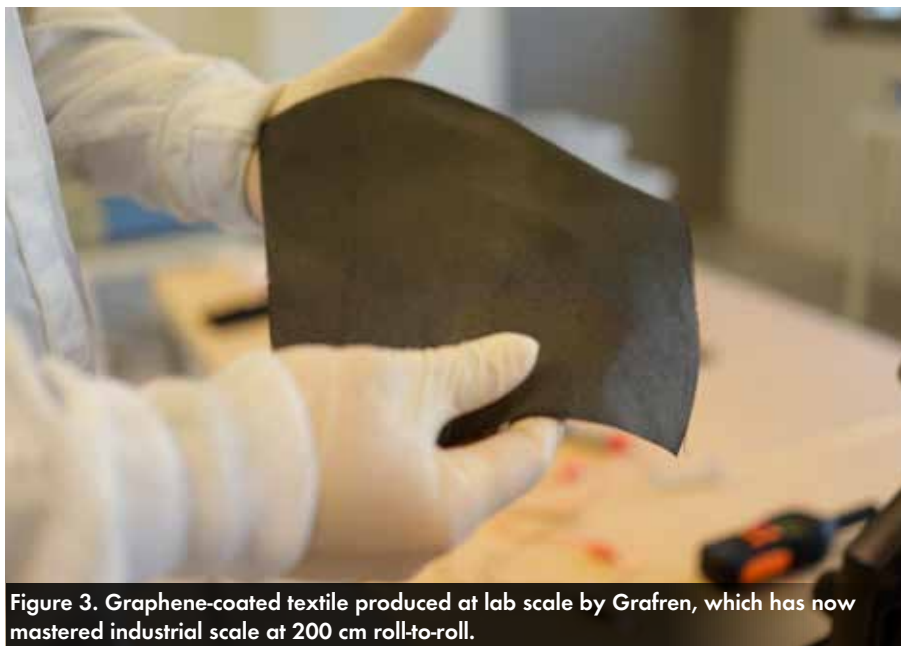
Further, Grafren's fiber-coating process can be applied to other 2D materials, Khranovskyy says, noting that Grafren already filed a patent related to this technology. "Those ideas which researchers are discussing on flat surfaces, they can be realized inside of fabric on individual fibers as well," he says.

Because of graphene's conductivity, Grafren's coated fabrics offer several functional capabilities. The fabrics can collect signals from the body to act as a biomonitor or biosensor; they provide thermal management, either removing or providing heat to an athlete depending on the surrounding conditions; they can function as a strain sensor if the graphene is coated onto a stretchable fabric (so that stretching changes conductivity); and they can function as pressure sensors or impact sensors by creating an electrically conductive channel from several fibers grouped together.

"Imagine shoes—the soles could measure pressure. The more points you have, you can actually measure pressure distribution" Khranovskyy says. "The shoe could also measure the force when you kick a ball. Or consider boxing gloves that could measure pressure. So any textile, any fabric, any clothing which is in contract may be active and may provide a signal about the force and the place where it was applied."

In addition to performance, such sensors could play an important role in athlete safety as well. "If we imagine any type of a sport activity where we have helmets, then the pressure sensors can be simply integrated in the lining," Khranovskyy says. Helmet-affixed sensors could provide valuable information for assessing player injuries, such as the strength of the hit, the area of the head where the impact was localized, and when the athlete gets up from the impact.

Khranovskyy says that one of the biggest challenges Grafren faces is the vast possibilities for graphene-coated fibers—



Credit: Grafren

Figure 3. Graphene-coated textile produced at lab scale by Grafren, which has now mastered industrial scale at 200 cm roll-to-roll.

just deciding which direction to pursue can be difficult.

"From our experience, graphene provides several functions to textiles, which enable 10 times more directions of further product development, and the amount of products is even 10 times more." Grafren works with its customers to tailor its graphene-coated textiles to a particular application.

"For every product the value may be different. So in order to commercialize it, we have to really identify what is it exactly customers would like to enable," Khranovskyy says.

A potential direction that Grafren currently is working on with one its customers is to develop heatable clothing. The company already developed a functioning prototype of its graphene-coated heated textile—although it looks nearly indistinguishable from a standard athletic textile, the fabric is coated with graphene and incorporates conductive threads running throughout the fibers that, with the press of a button on a connected energy source, gently warm the fabric.

Such fabrics have applications for athletes in cold environments but also could provide warming at specific locations for therapeutic purposes, to enhance athletic recovery.

Thermal management is a hot topic in sports apparel, with other similar types of developments using fabrics coated with carbon fibers or incorporating ceramic nanoparticles to warm or cool athletes depending on the surrounding environment.¹⁶

Grafren's conductive textiles demonstrate just one possible application of graphene in sports, for which there is diverse potential due to the material's long list of desirable properties.

The Graphene Flagship, a joint research venture funded by the European Commission, already helped develop several other sports-related applications of graphene, including an impact-resistant graphene-coated motorcycle helmet,¹⁷ a transdermal patch to monitor fitness using graphene optical sensors,¹⁸ and a graphene-based lubricant for auto and motorcycle engines.¹⁹

Sensing the future: Optimizing performance and enhancing safety

Sports equipment was once designed solely for mechanical performance, but advanced materials offer new design freedoms and thus new functionalities to change how sports are played, experienced, and enjoyed.

"Now, within the past decade or so, we're starting to get multifunctionality, so the materials offer say thermal control or odor control, or they're able to sense things like the pH of your sweat or your heartbeat. And that's an area really where ceramics and glasses can play an important role and already do in sports," says Jud Ready, principal research engineer at Georgia Tech Research Institute, deputy director of innovation initiatives at the Institute for Materials, and adjunct professor in the School of Materials Science and Engineering at Georgia Institute of Technology. Ready teaches a popular Georgia Tech course on materials science and engineering in sports.

The power of sensors is that they provide physical data about how athletes play sports, to inform sports strategy and improve safety, as well as physiological data about how athletes' bodies function during and after athletic exertion, to enhance performance. While vast sensors and sensing technologies are already widely incorporated into motorsports—such as ceramic oxygen sensors in motor engines—technological developments have more recently enabled biosensors and biomonitors to track a vast array of individual parameters of athletes as they practice, compete, and recover.

Devices that monitor physical performance and safety collect data on an athlete's position, motion, impact, and biomechanical forces. These devices include wearable devices to monitor head injuries in contact sports to prevent concussion or traumatic brain injury, such as helmets, headbands, caps, or neck-worn collars.

For example, several companies developed mouthguards with embedded sensors to monitor head impacts. One such device contains embedded sensors that detect collision intensity, providing a visual readout with front-facing LED

lights that can alert trainers and coaches about dangerous impacts. Other developments include wearable sensors to monitor joint mechanics during play as a means to prevent injury.²⁰

Other sensing devices monitor athletes' physiological status to optimize performance, collecting data on parameters such as heart rate and sleep. Optical sensors to monitor heart rate are relatively well-established technologies, with new trends toward development of skin-worn patches as well as integrated textiles that can measure heart rate. Yet while heart rate provides a global measure of physical activity and exertion, it cannot provide information on the response in specific muscles—data that is important for professional athletes seeking to optimize their performance.

In response, an emerging trend is monitoring muscle oxygen saturation to inform how specific muscle groups respond to activity, using optical technologies to measure oxygenation of blood in muscles with near-infrared light.²⁰

While more widely available wearable sensors currently measure these physical and physiological parameters, there also exists vast potential to monitor biochemical parameters that affect athletes' performance, and many sensors are being developed in this space as well.

Such devices can sample sweat or saliva to measure biochemical signals such as electrolytes, enzymes, and neurochemicals, providing a means to noninvasively monitor health and performance in real time. These types of biosensors include mouthguards that detect chemicals in saliva that indicate muscle fatigue, contact lens sensors for ocular diagnostics, or skin-based sensors to monitor neurochemical markers of stress in sweat.

Biochemical sports sensors also offer corollary functions within medical diagnostics, and some of these sensors are adapted from existing medical technologies. For example, healthcare company Abbott (Chicago, Ill.) developed a commercial wearable continuous glucose monitor for athletes. Applied to an athlete's arm, the small wearable device, called Libre Sense, uses a thin filament inserted just under the skin to measure glucose levels in the fluid surrounding cells.

Game-changers: How ceramic and glass materials enhance . . .

“The biosensor is designed to provide a glucose monitoring experience that will enable athletes to understand the efficacy of their nutrition choices during training and competition,” according to company’s website.²¹

The device is similar to that used by diabetics, but it is tailored to athletes by providing more frequent minute-by-minute glucose readings. “It will therefore inform athletes about how to fuel appropriately, to fill their glycogen stores prior to a race and to know when to replenish during a race to maintain athletic performance,” the company’s website explains.

Conversely, technologies developed to monitor athletic parameters are often not confined to sports contexts, as these innovations can extend into markets and aspects of life beyond sports as well. For example, innovations in sensor technologies to track athletes often can be adapted to monitor or manage health aspects in a medical context, providing much

wider value to these technologies.

That is something Grafren CEO Erik Khranovskyy recognizes for its graphene-coated textile sensor technologies. “So all the sensors which I described, they can bring a lot of value to one athlete and one nation once per four years,” he says. “On the other hand, they can bring a lot of value to millions of people on a longer-term perspective.”

Despite the technological capability to measure and collect such rich data, however, interpretation to the athlete often lags behind. For instance, in the case of Abbott’s Libre Sense, blood sugar and performance have a complicated relationship—low blood sugar levels do not necessarily mean performance will suffer, and conversely elevated blood sugar levels will not ensure maximum athletic performance, especially in high-functioning endurance athletes. These parameters are variable with time, exertion, and athlete, so interpretation of

the data is nuanced. More extensive datasets and further data analyses are needed to improve data interpretation to an athlete’s performance.²²

Despite the lag in data interpretation, the possibility to track and collect such rich data for athletic performance will continue to push development of all kinds of sensors across the sports industry in the future. These trends offer significant potential for the ceramic and glass components that enable these sensors, monitors, and electronic components with the lucrative sports industry.

Similarly, many wearable devices and sensors require a power source, another area that offers significant potential for ceramic and glass materials in the future of the sports industry. The continued push for batteries with higher power density that offer longer life in smaller form, allowing smaller devices that can provide more functionality, provides opportunity for innovation with new

PLAYING THROUGH A GLOBAL PANDEMIC

The global COVID-19 pandemic has affected businesses around the world, disrupting supply chains for seemingly everything and drastically impacting the workforce. Not surprisingly, the world of sports was not spared.

Cancellation of major sports events in early 2020 were some of the earliest indications to many people of just how serious the pandemic was, as trends within sports often reflect larger trends in society. Gyms and fitness centers closed, entire sports seasons were missed, and perhaps most telling, the Tokyo 2020 Olympic Games were postponed until 2021.

While the cancellations, closures, and postponements had a negative economic impact on the sports industry, the pandemic’s effects on sports were not all negative.

“If you would have asked me 18 months ago, pre-COVID, the tennis business was struggling,” says Jeff Bardsley, Head’s vice president of marketing for racquet sports for North America. “Participation was down, people were playing other sports, people weren’t engaged in sports, period. I think all sports for the most part were struggling.”

The pandemic shifted that dynamic for many sports as people worldwide increasingly turned to sports and outdoor activities for physical as well as mental health benefits. That statement is particularly true for sports that offer the ability to play while maintaining social distance—games like golf, tennis, and disc golf saw increased participation and market value as a result of the pandemic.

In the U.S., golf experienced a 2% increase in the number of individuals playing at least one round of golf in 2020 compared to 2019, the largest increase in the game in nearly two decades. And this participation is not limited to only seasoned players pulling their clubs out of the closet, according to a *CNBC* report.^a “‘New participants are increasingly younger; they’re hooked on the game and they want to get better,’ David Maher, CEO of golf conglomerate Acushnet Holdings, said on the company’s second-quarter earnings call with analysts in August. ‘A lot of the energy is coming from avid dedicated players who are simply playing more and consistently; more juniors, more women, more younger [players], and more families.’”

For golf, that increased enthusiasm for the sport translated to manufacturers and retailers as well—Acushnet, the company that owns popular golf brands Titleist and FootJoy, reported 117.1% growth in net sales in the U.S. in the second quarter of 2021. Golf brand Callaway and sporting goods store Dick’s also noted growth in golf sales.^a

Tennis also saw pandemic-fueled gains, with participation rising 22% in the U.S. in 2020 compared to 2019.^b Bardsley says Head has had difficulty keeping up with the surge in demand. “We have struggled over the last 18 months to try and keep product on shelves. We’re the largest producer of tennis balls in the world, and we can’t supply our retailers in the U.S., North America, globally with tennis balls.”

Bardsley is hopeful that the increased interest will not wane with the pandemic. “From the trends that we’ve seen so far in sporting goods sales, I definitely perceive that as an upward trend... In my 29 years in business, I’ve never ever seen anything like this—so I’m hopeful for the sport.” ¹⁰⁰

^aCNBC, “Golf’s growth in popularity is much bigger than a pandemic story,” September 26, 2021, *CNBC*. <https://www.cnbc.com/2021/09/26/callaway-dicks-sporting-goods-score-with-growth-of-golf.html>

^bM. Futterman, B. Pennington, “The pandemic drove people to tennis and golf. Will they keep playing?” March 11, 2021, *New York Times*. <https://www.nytimes.com/2021/03/11/sports/tennis/tennis-golf-participation-pandemic.html>

materials. For example, the Whoop fitness tracker is powered by a slim yet high-density battery that continuously monitors heart rate, sleep, recovery, and more. The battery gets a boost from technology by Sila, a company that developed a silicon powder that replaces conventional graphite anodes with higher-density silicon anodes, offering up to 20% higher energy density.²³ Other batteries technologies and developments are sure to find their way into wearable sports sensors as well.

Yet another possibility could be ditching the power source altogether, and instead leaning on self-powered piezoelectric materials to provide power to wearables and sensors, as the ability to convert mechanical energy to electrical energy is well-suited for sports contexts. While the heyday for incorporating piezoelectric fibers into sports equipment—which included not only Head’s Intelligence tennis rackets, but also various skis, snowboards, mountain bicycles, baseball bats, and golf clubs—seems to have passed (as this equipment often relied more heavily on marketing rather than enhanced performance to sell piezoelectrics’ possibilities²⁴), new future potential for the materials might be found in the ability to power sports sensors.

Fans get in the game

Beyond enhancing athletic performance and improving safety, sensors offer another function that is likely to be significant in the future of sports—the fan experience.

“You can use that same data that you’re collecting to measure athletic performance, health, wellness and prevention, to create an immersive fans’ experience,” says Leslie Saxon, professor of medicine and executive director of the University of Southern California’s Center for Body Computing, in a *BBC News* article.²⁵ “What if I record my own heart rate while watching my favorite football player play, looked at my response and compare it to his response on the field?”

Digital technologies to enhance fan engagement experienced a significant boost since the start of the COVID-19



American professional golfer Bryson DeChambeau, above, uses graphite shafts made from carbon fiber in all his clubs. His choice contrasts with other professional golfers, who generally only use graphite shafts in their driver and other wood-type clubs.

Credit: Jacob Grifton, Flickr (CC BY-SA 2.0)

pandemic, as health and safety precautions shifted in-person experience of sports events to virtual platforms (see sidebar: *Playing through a global pandemic*). Continued investments in the infrastructure to support streaming platforms, digital content, and even augmented and virtual reality experiences will continue moving the trend forward, incorporating the data provided by athlete-worn biosensors to further engage fans.

“As this technology matures, there will be more and more biosensors out there,” Saxon says in the article. “It is truly the next frontier in sports and technology.”

Ensuring fair play

As technology continues to play an increasing role in sports, moral questions begin to arise. One long-standing question involves equity in access, as expensive technologies introduce disparities between those who can afford the devices and those who cannot. Yet another quandary surrounds the potential for technologies to extend beyond simply sensing and instead offer functional improvements to athletic performance.

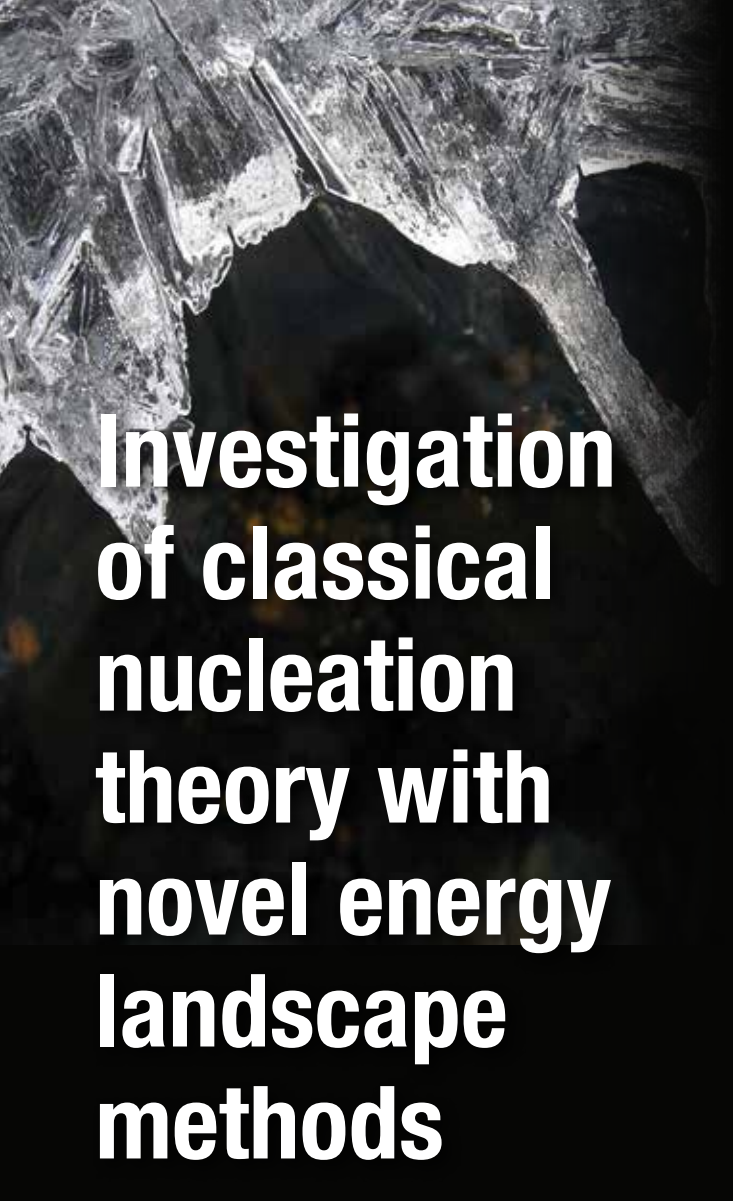
“What about if there’s an opportunity to make an implant on your bone that could make it more structurally sound so you could run further, or it’s a piezoelectric sensor that measures the stress in the bone?” says Ready. “Maybe that’s bad to use in competition because it’s giving feedback that you can actively use in competition, but maybe it’s useful during rehabilitation—so is it okay in one scenario and not in the other?”

The line between where materials enhance athletic performance and where materials provide an unfair advantage or artificially exaggerate human capabilities is colored in various shades of gray. And it is often difficult to discern or quantify just how much advantage a technology might provide to an athlete, further complicating the picture.

Yet Ready suggests that sports are based on advantage and competition. “That’s the whole point of sports—you’re trying to prove that you’re better than somebody else,” Ready says. Technologies provide means to improve the game, and as long as they follow the rules, innovation is fair game. “That is, I think, what materials science tries to do, is to give you an unfair competitive advantage. But we do it in a rules-compliant way, whether that rule does not yet exist, and therefore we’re in compliance with it, or because we go right up to the boundary,” he says.

So what does the future of sports look like? Despite debates about the fairness of new technologies, materials science offers the ability to enhance and improve existing aspects of sports as well as innovate in new and sometimes unexpected ways. Technology will continue to infiltrate sports, in some ways enhancing athletic performance and improving the safety and fan experience of the game. Athletes, enabled by technology, will continue to get better, setting new world records—and those feats of athleticism will be backed by materials science. ¹⁰⁰

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Investigation of classical nucleation theory with novel energy landscape methods

By Collin J. Wilkinson & John C. Mauro

The methods and the software developed in this work offer a promising step to gain insights into the fundamental nature of glass-ceramic nucleation and the validity of classical nucleation theory.

Crystallization (and by extension nucleation) is a critical process in all material systems that determines how a material will form. Manufacturers have generated billions of dollars of economic development by creating new materials through manipulation of crystallization.

There are two phenomenological steps in the process of phase transformation from a supercooled liquid to a crystal: a nucleation step and a crystal growth step. The growth step is described well by Wilson-Frenkel's theory,¹ but the underlying physics of nucleation remains elusive. For glass-

ceramics, or composite materials consisting of crystals in a glassy matrix, having a clear idea of how nucleation occurs would aid significantly in finding the optimal thermal history for the desired crystallite distribution.

In this study, we employed first principles and energy landscape methodologies to provide insights into the fundamental nature of nucleation for the barium disilicate system. Our exploration also enabled a test of classical nucleation theory, which is the most common approach to understanding nucleation. Although it is not the first study to computationally examine the theory's validity,²⁻⁴ it is the first independent parameterization of each variable in an attempt to calculate the resulting nucleation rate.

Challenges in optimizing glass-ceramic design

The difficulty in designing a glass-ceramic is apparent when considering the high dimensional phase space of parameters that can be adjusted. A glass system has d dimensions over which it can be optimized, where d is the number of components ($d-1$ mutually independent compositional dimensions and at least one thermal history dimension). A glass-ceramic system has four additional phase dimensions (two for the nucleation/growth temperatures and two for nucleation/growth times) that require optimization. Therefore, a glass-ceramic system has $d+4$ dimensions over which the system must be optimized.

There are some tools such as topological constraint theory⁵ that can help optimize over the glassy space; however, the four additional dimensions (for nucleation and growth temperatures/times) remain poorly understood. Thus, designing computational methods to easily optimize over this large space is of utmost importance to developing a new generation of custom glass-ceramic materials.

Crystal nucleation is historically difficult to simulate computationally because the phenomenon happens on spatial scales of nanometers and over many orders of magnitude of time scales. Recent approaches using grand canonical Monte Carlo successfully predicted the short time dynamics of nuclei formation while enabling greater thermodynamic insights⁶; however, it remains computationally expensive.² Molecular dynamics also falls short in simulating crystal nucleation of glass-forming systems due to the need for longer spatial and temporal scales to capture nucleation effects accurately.

The energy landscape offers another approach for simulating crystal nucleation. The energy landscape is a high dimensional construct that relates the location of every atom to the total energy of the system. It has become crucial to studies of biomolecules, glasses, and catalysts⁷⁻⁹ because it can show the relevant atomic configurational changes and can calculate the associated changes in kinetics and thermodynamics.

An energy landscape can be thought of as a $3N$ -dimensional hyperspace, where each coordinate represents an x , y , or z position of the N atoms considered. As an energy landscape is mapped, most configurations become unnecessary to record as they represent energies much higher than the local minima. These local minima are often called inherent structures (IS), and these states control the thermodynamics of the system. The kinetics of the system are then controlled by the lowest energy saddle point between each pairwise set of IS. Using this information, we can decrease the complexity of the system by just considering the IS and the saddle points.

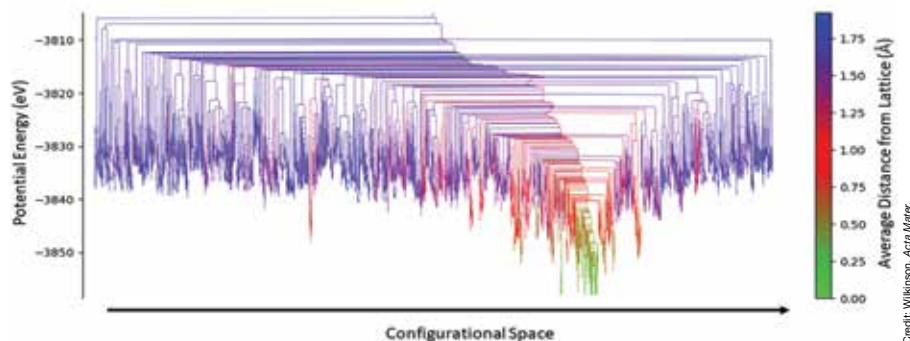


Figure 1. The energy landscape for a barium disilicate glass-ceramic shown in a disconnectivity graph. The x-axis is an arbitrary phase space and the y-axis is the potential energy calculated from the Pedone potentials.¹⁴ Each terminating line represents an inherent structure and the point where two lines meet represents a transition point. The colors are indicative of the crystallinity. Reproduced from Ref. 15 with permission of the author.

Exploring glass-ceramic nucleation through the energy landscape

In this study, we explored the energy landscape of a barium disilicate system capturing the glassy and crystalline basins. We chose barium disilicate because it is a commonly studied glass-ceramic with multiple reliable experimental datasets in literature.^{10–12}

The energy landscape for this investigation was generated using the software ExplorerPy,¹³ starting with the orthorhombic barium disilicate crystalline structure. The mapped landscape then allowed for the free energy difference and the kinetic transition rates to be calculated directly. The interfacial free energy was obtained from molecular dynamics simulations. The Pedone potentials¹⁴ were used and the volume of the cell was fixed, due to simulation instability when pressure was fixed. The resulting energy landscape is seen in Fig. 1.¹⁵

Once the temperature-dependent parameters were derived from the landscape, they were used to calculate the nucleation rates in classical nucleation theory. Classical nucleation theory is given by the product of a kinetic function (K) and a thermodynamic term,

$$I = K \exp [-W/kT] = K \exp [-(16\pi \sigma^3)/(3(\Delta G)^2 kT)] \quad (1)$$

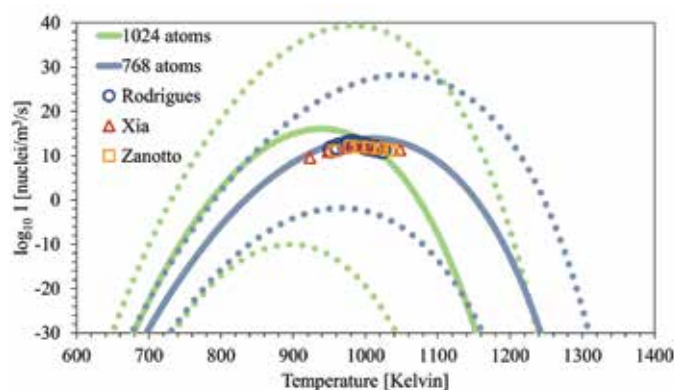


Figure 2: The nucleation curve for barium disilicate as predicted using the model presented in this work. The data referenced can be found in Refs. 12, 18, and 19. The dotted lines show uncertainty for the prediction calculated from the interfacial energy. Reproduced from Ref. 15 with permission of the author.

In classical nucleation theory, the work (W) needed to generate a spherical isotropic nucleus¹ consists of a volume term related to the free energy difference of a crystal and glass (ΔG), as well as a surface energy term (σ). By determining these three temperature-dependent functions, prediction of the overall nucleation rate is possible. Though there are existing methods in literature to approximate each of these quantities, the approximations often include large errors and assumptions about the behavior of the system.¹⁶ Experimentally, the kinetic function is often approximated with the Stokes-Einstein relationship, the ΔG term is calculated from heat capacity curves, and σ is fitted.¹⁶

Classical nucleation theory is known for giving widely varying results depending on how the parameters are determined.^{1,6,17} When crystal nucleation rates are calculated, it is not atypical to be 10+ orders of magnitude off from experimental values. The inability to get accurate predictions consistently for nucleation curves means that choosing an appropriate nucleation temperature must be done empirically, which can prove to be one of the most challenging and time-consuming aspects for optimizing the design of a glass-ceramic.

As shown in Fig. 2, the resulting nucleation curves agree well with the experimental nucleation rates. However, when the individual properties are compared, the interfacial free energy and kinetics show disagreement with the experimental calculations while the thermodynamic barrier shows good agreement.

Conclusions

This study is, as far as the authors know, the first reporting of a real energy landscape for a complicated glass-ceramic system. In the future, this model could be used for either developing commercial glass-ceramics or for predicting the critical rate needed to keep a liquid glassy. Additionally, the technique presented here can provide additional insights into the physics of nucleation and the validity of classical nucleation theory.

About the authors

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Editor's note

Wilkinson will present the 2021 Kreidl Award Lecture at the virtual Glass & Optical Materials Division Annual Meeting on Dec. 15, 2021. Learn more about the conference at <https://ceramics.org/pacrim14>.

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Sustainability is key at



From left, moderator Kayleigh Porter talks with Shawn Allan, Dror Danai, and Jesse Blacker about the commercial viability of various ceramic additive manufacturing techniques.

After a year of going virtual in response to the COVID-19 pandemic, Ceramics Expo experienced a highly successful return as a live event on Aug. 31–Sept. 1, 2021, in Cleveland, Ohio.

The leading annual supply chain exhibition and conference for the advanced ceramic and glass industry welcomed dozens of exhibitors and hundreds of attendees to its new location at the Huntington Convention Center of Cleveland. During the two-day event, more than 30 expert speakers shared insights into the latest developments in applications and manufacturing of technical ceramics and the critical role that they will play in “enabling a clean, efficient, and electrified future.”

“Ceramics Expo 2021 was a resounding success. It was fantastic for ACerS leadership and staff to be able to interact and engage with many of our Corporate Partners and members in person. This show continues to help us meet the need of our industrial members to interact with existing and prospective customers,” says Mark Mecklenborg, ACerS executive director.

Day 1 of Ceramics Expo focused on research and initiatives to improve sustainability in ceramic and glass manufacturing, particularly through developing new materials and improving system infrastructures.

The first panel discussion kicked off the day by exploring sustainability in supply chains, a topic that has received increased attention this past year due to the COVID-19 pandemic revealing weaknesses in the current supply systems. Later sessions throughout the day covered topics such as facilitating environmentally friendly practices, the potential role of flow batteries in the future of energy storage, and understanding the implications of emission control regulations on clean mobility technology.

Day 2 of Ceramics Expo also looked at improving sustainability, but the focus this day was on processes for fabricating materials.

The first panel discussion of Day 2 considered how to bridge the gap between research & development and commercial viability of ceramic additive manufacturing. Later sessions throughout the day

covered topics such as improving efficiency of sintering processes, using powder X-ray diffraction for microstructural analysis, and improving properties of ultrahigh-temperature ceramics.

Throughout the sessions, many panelists mentioned the challenge of finding people to fill labor shortages in the industry. During the last panel session of Day 1, Jennifer Benson (Raytheon Technologies, chief engineer), Elizabeth Dickey (Carnegie Mellon University, Teddy & Wilton Hawkins Distinguished Professor and Department Head of Materials Science and Engineering), and Eileen De Guire (ACerS, director of technical content and communications) discussed how the gender gap in STEM fields can contribute to this challenge.

“If we’re only pulling from half of the population, we’re not going to make it,” Dickey says.

After giving some statistics on the underrepresentation of women in STEM, they offered several solutions for closing the gender gap. For example, creating more awareness of what materials scientists do, so women will want to enter the field; offering flexible work schedules, so women can start a family while pursuing their career; and launching programs to help women transition back into the field following a career break.

Join us at the 7th annual Ceramics Expo, which will take place at the Huntington Convention Center of Cleveland on Aug. 29–31, 2022.

New for 2022—Thermal Technologies Expo

Aug. 29–31, 2022

Co-located with Ceramics Expo

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- Focused workshops on specific thermal management challenges
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www.thermaltechexpo.com

THERMAL
TECHNOLOGIES EXPO



Virtual Conference

Dec. 12–17, 2021 | ceramics.org/pacrim14

PACRIM 14TH PACIFIC RIM CONFERENCE ON CERAMIC AND GLASS TECHNOLOGY

including **Glass & Optical Materials Division Meeting (GOMD 2021)**



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.

We anticipate strong participation of colleagues from cooperating societies, including CerSJ, KCerS, CCS, AusCerS, and other ceramic societies from around the world. ACerS Glass & Optical Materials Division will host its Division meeting at PACRIM14.

PACRIM PLENARY SPEAKERS

MONDAY, DEC. 13

**MELISSA ORME**

Vice president, Boeing Additive Manufacturing,
The Boeing Company, USA

*Recent advances in the disruptive technology
of additive manufacturing at Boeing*

**JAW-SHEN TSAI**

Professor, Tokyo University of Science, Department of
Physics, Japan; Laboratory Head of Macroscopic
Quantum Coherence Research, RIKEN Center for
Quantum Computing (RQC), Japan

Superconducting quantum computer and its future issues

**MARY ANNE WHITE**

Harry Shirreff Professor of Chemical Research (Emerita),
Department of Chemistry,
Dalhousie University, Canada

Thermal properties of advanced ceramics

**SANG IL SEOK**

Distinguished Professor, Laboratory for Energy
Harvesting Materials and Systems (LEHMS), School of
Energy and Chemical Engineering, Ulsan National
Institute of Science and Technology (UNIST), Korea

*Halide perovskite-based photovoltaics—
from materials to devices*

PACRIM 14 TECHNICAL PROGRAM

- Multiscale Modeling, Simulation, and Characterization
- Innovative Processing and Manufacturing
- Nanotechnology and Structural Ceramics
- Multifunctional Materials and Systems
- Ceramics for Energy Systems
- Ceramics for Environmental Systems
- Biomaterials, Biotechnologies, and Bioinspired Materials

GOMD 2021 TECHNICAL PROGRAM

- S1: Fundamentals of the Glassy State
- S2: Glass and Water: Degradation of Amorphous Materials
- S3: Optical and Electronic Materials and Devices —
Fundamentals and Applications
- S4: Glass Technology and Cross-cutting Topics
- S5: Glass Education

GOMD 2021 AWARD SPEAKERS

TUESDAY, DEC. 14

GEORGE W. MOREY AWARD

**Walter Kob**

Professor,
University of
Montpellier,
France

Glass: We love it, but it breaks

WEDNESDAY, DEC. 15

NORBERT J. KREIDL AWARD FOR YOUNG SCHOLARS

**Collin
Wilkerson**

The Pennsylvania
State University,
USA

*Confirming classical nucleation
theory with novel energy landscape
methods*

THURSDAY, DEC. 16

VARSHNEYA GLASS TECHNOLOGY AWARD

**Heike Ebendorf-
Heidepriem**

Professor,
University of
Adelaide,
Australia

*Nanocrystal doped glass and
fibers: Fabrication challenges and
opportunities for novel photonics
applications*

THURSDAY, DEC. 16

ALFRED R. COOPER AWARD

**Efstratios I.
Kamitsos**

Director of
research,
Theoretical and
Physical Chemistry
Institute of the

National Hellenic Research
Foundation, Athens, Greece

Structure and ion dynamics in glass

REGISTER TODAY! JAN.19–21, 2022

ELECTRONIC MATERIALS AND APPLICATIONS 2022

DoubleTree by Hilton | Orlando, Fla., USA | ceramics.org/ema2022 | Hybrid Conference

ORGANIZED BY THE ACERS ELECTRONICS AND BASIC SCIENCE DIVISIONS

ACerS is pleased to announce the addition of a hybrid option for EMA '22 to allow participation by individuals who cannot attend in-person due to travel restrictions. We plan to provide a hybrid solution that will incorporate prerecorded talks from virtual attendees into the live onsite programming. All live sessions will be recorded for all attendees to view at the conclusion of the live conference, available until March 31, 2022.

Electronic Materials and Applications 2022 (EMA 2022) is an international conference focused on electroceramic materials and their applications in electronic, electrochemical, electromechanical, magnetic, dielectric, biological, and optical components, devices, and systems. Jointly programmed by the Electronics Division and Basic Science Division of The American Ceramic Society, EMA 2022 will take place at the DoubleTree by Hilton Orlando at Sea World, Jan. 19–21, 2022.

EMA 2022 is designed for scientists, engineers, technologists, and students interested in basic science, engineering, and applications of electroceramic materials. Participants from across the world in academia, industry, and national laboratories exchange information and ideas on the latest developments in theory, experimental investigation, and applications of electroceramic materials.

Students are highly encouraged to participate in the meeting. Prizes will be awarded for the best oral and poster student presentations.

The technical program includes plenary talks, invited lectures, contributed papers, poster presentations, and open discussions. EMA 2022 features symposia focused on dielectric, piezoelectric, pyroelectric, magnetoelectronic, (multi)ferroic, quantum, relaxor, optoelectronic, and photonic ceramics; complex oxide thin films, heterostructures, and nanocomposites; semiconductors; superconductors; ion-conducting ceramics; 5G materials for millimeter-wave technology; and functional biological materials. Other symposia emphasize broader themes covering processing, microstructure evolution, and integration; effects of surfaces and interfaces on processing, transport, and properties; point defects, dislocations, and grain boundaries; mesoscale phenomena; and advanced characterization and computational design of electronic materials.

EMA includes several networking opportunities to facilitate collaborations for scientific and technical advances related to materials, components, devices, and systems. The Basic Science Division will again host a tutorial session in addition to the regular conference programming.

The grand finale of the meeting will again be Failure: The Greatest Teacher. We invite anyone interested to submit a brief abstract for this educational and engaging event that concludes the meeting.

Please join us in Orlando, Fla., to participate in this unique experience!

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TECHNICAL PROGRAM

- S1 – Characterization of Structure–Property Relationships in Functional Ceramics**
- S2 – Advanced Electronic Materials: Processing Structures, Properties, and Applications**
- S3 – Frontiers in Ferroic Oxides: Synthesis, Structure, Properties, and Applications**
- S4 – Complex Oxide Thin Films and Heterostructures: From Synthesis to Strain/Interface-engineered Emergent Properties**
- S5 – Mesoscale Phenomena in Ferroic Nanostructures: From Patterns to Functionalities**
- S6 – Emerging Semiconductor Materials and Interfaces**
- S7 – Superconducting and Related Materials: From Basic Science to Applications**
- S8 – Structure–Property Relationships in Relaxor Ceramics**
- S9 – Ion-conducting Ceramics**
- S10 – Point Defects and Transport in Ceramics**
- S11 – Evolution of Structure and Chemistry of Grain Boundaries and Their Networks as a Function of Material Processing**
- S12 – 5G Materials and Applications Telecommunications**
- S13 – Agile Design of Electronic Materials: Aligned Computational and Experimental Approaches and Materials Informatics**
- S14 – Functional Materials for Biological Applications**
- S15 – Advanced Microelectronics**

REGISTER TODAY! JAN. 23–28, 2022

46TH INTERNATIONAL CONFERENCE AND EXPOSITION ON ADVANCED CERAMICS AND COMPOSITES

Hilton Daytona Beach Resort and Ocean Center | Daytona Beach, Fla., USA | Hybrid Conference | ceramics.org/icacc2022

ORGANIZED BY THE ENGINEERING CERAMICS DIVISION OF THE AMERICAN CERAMIC SOCIETY

We are pleased to announce that the 46th International Conference & Exposition on Advanced Ceramics & Composites (ICACC 2022) will be held from Jan. 23–28, 2022, in Daytona Beach, Fla. This conference has a strong history of being the preeminent international meeting on advanced structural and functional ceramics, composites, and other emerging ceramic materials and technologies. The Engineering Ceramics Division (ECD) of The American Ceramic Society has organized this esteemed event since 1977. Due to the high quality of technical presentations and unique networking opportunities, this event has achieved tremendous worldwide interest and has attracted active participation from ceramic researchers and developers from the global technical community thanks to the dedication and support of our membership.

We look forward to seeing you in Daytona Beach, Fla., in January 2022. Check out our hybrid option if you are unable to travel.

Palani Balaya, program chair, ICACC 2022
National University of Singapore | mpepb@nus.edu.sg

PLENARY SPEAKERS

Monday, Jan. 24

THOMAS SPECK, University of Freiburg and Cluster of Excellence Living, Adaptive and Energy-autonomous Materials Systems (livMatS), Germany
Plant materials systems and structures: Bio-inspiration for a “greener” technology in the 21st century

Y. SHIRLEY MENG, Zable Chair Professor in Energy Technologies and professor in Materials Science & NanoEngineering, University of California San Diego, USA

Designing better ceramic materials for future batteries

GLOBAL YOUNG INVESTIGATOR AWARD

Sunmi Shin, National University of Singapore, Singapore

Thermal engineering using infrared photonic structures: Probing coherent thermal emission in a single nano-object

MECHANICAL PROPERTIES OF CERAMICS AND GLASS 2022 SHORT COURSE

Jan. 27–28, 2022 | 8:30 a.m. – 5 p.m.

Location: In conjunction with ICACC2022, Hilton Daytona Beach Resort and Ocean Center, Daytona Beach, Fla., USA

Instructor: **George D. Quinn**, NIST

SYMPOSIA

- S1: Mechanical Behavior and Performance of Ceramics and Composites**
- S2: Advanced Ceramic Coatings for Structural, Environmental, and Functional Applications**
- S3: 19th International Symposium on Solid Oxide Cells (SOC): Materials Science and Technology**
- S4: Armor Ceramics – Challenges and New Developments**
- S5: Next Generation Bioceramics and Biocomposites**
- S6: Advanced Materials and Technologies for Rechargeable Energy Storage**
- S7: 16th International Symposium on Functional Nanomaterials and Thin Films for Sustainable Energy Harvesting, Environmental and Health Applications**
- S8: 16th International Symposium on Advanced Processing and Manufacturing Technologies for Structural and Multifunctional Materials and Systems (APMT16)**
- S9: Porous Ceramics: Novel Developments and Applications**
- S10: Modeling and Design of Ceramics and Composites**
- S11: Advanced Materials and Innovative Processing Ideas for Production Root Technologies**
- S12: On the Design of Nanolaminated Ternary Transition Metal Carbides/Nitrides (MAX Phases) and Borides (MAB Phases), Solid Solutions thereof, and 2D Counterparts (MXenes, MBenes)**
- S13: Development and Applications of Advanced Ceramics and Composites for Nuclear Fission and Fusion Energy Systems**
- S14: Crystalline Materials for Electrical, Optical, and Medical Applications**
- S15: 6th International Symposium on Additive Manufacturing and 3D Printing Technologies**
- S16: Geopolymers, Inorganic Polymers, and Sustainable Materials**
- S17: Advanced Ceramic Materials and Processing for Photonics and Energy**
- S18: Ultrahigh-temperature Ceramics**

REGISTER TODAY! March 15–18, 2022

17TH BIENNIAL WORLDWIDE
CONGRESS ON REFRACTORIES

THE UNIFIED INTERNATIONAL TECHNICAL CONFERENCE ON REFRACTORIES

17th Biennial Worldwide Congress on Refractories
Hilton Chicago Chicago, Ill., USA

UNITECR 2022

HOSTED BY:



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The Unified International Technical Conference on Refractories (UNITECR) is a biennial international conference that contributes to the progress and exchange of industrial knowledge and technologies concerning refractories.

SYMPOSIA TITLES

- Advances in Installation Techniques, Manufacturing, and Equipment
- Advances in Monolithic Technology
- Iron and Steelmaking Refractories
- Modeling and Simulation of Refractories
- New Developments in Refractory Formulation
- Nonoxide Refractory Systems
- Raw Materials
- Refractories for Aluminum
- Refractories for Cement and Lime
- Refractories for Glass
- Refractories for Other Applications
- Refractories for Petrochemical Applications
- Refractory Education
- Refractory Characterization and Testing
- Refractory Technology and Techniques for Energy Savings
- Safety, Environmental Issues, and Recycling
- Use of Artificial Intelligence, Machine Learning, and Big Data in Refractory Technology
- Refractory Student and Young Professionals Symposium
- Theodore J. Planje Award Symposium

TENTATIVE SCHEDULE OF EVENTS

Tuesday, March 15, 2022

Welcome event 6–10 p.m.

Wednesday, March 16, 2022

Opening ceremony 8:30–9:30 a.m.
Exhibits 9:30 a.m. – 7 p.m.
Technical sessions 9:30 a.m. – 5:30 p.m.
Exhibit reception and posters 5–7 p.m.

Thursday, March 17, 2022

Exhibits 9:30 a.m. – 4:30 p.m.
Technical sessions 8 a.m. – 5 p.m.
Banquet 7–10 p.m.

Friday, March 18, 2022

Technical sessions 8 a.m. – 12:30 p.m.
Lunch/Panel discussions/Closing 12:30–5:30 p.m.

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International Journal of
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Lithography-based additive manufacturing of ceramics for orthopedic joint implants: A focus on the tribology

During the last few decades, additive manufacturing became more popular in the biomedical field because of the ability to create complex shapes and porous or semiporous geometries without extra steps in the production process. An increasing number of printed metal and polymer products are well-established in the market, and quite a few printed ceramic and composite products are gaining interest as well.

Stereolithography is one of the most used additive manufacturing techniques for ceramic materials. Based on selectively photopolymerized ceramic-loaded slurries, this technology allows manufacturers to obtain highly dense final parts (around 99%), as well as good shape accuracy, with a lateral resolution of around 20–30 μm .

Inspired by the benefits of stereolithography, our work aims to create entirely ceramic implants for joint replacements. Implants made of metal can be related to allergies or undesired reactions, and due to their lower hardness and poor tribological behavior, doctors often prefer metal–ceramic composite implants instead. However, composite implants can lead to multicomponent interfaces that result in weak points, and that is why entirely ceramic implants are desirable.

To ensure biocompatibility, we selected materials with a long history in the orthopedic field for the current case study: alumina, zirconia, and two zirconia toughened alumina (ZTA) composites with 10 wt.% and 20 wt.% of zirconia, respectively.

We focused on analyzing the tribological behavior of the implants because the main movement of a joint is the continuous sliding between its two counterparts. Thus, studying the tribological behavior can help us to guarantee a part that experiences low wear. Tribological tests were performed in ambient air and liquid environments, using a bovine serum to mimic the in vivo conditions.

Friction coefficients under an average Hertz contact pressure of 800 MPa are in the range of 0.45–0.50 for alumina and ZTA, while in the order of 0.80 for zirconia. These values are comparable to the friction coefficients of conventionally processed alumina and ZTA parts in air conditions.¹ The zirconia coefficient, however, is significantly higher due to the well-known tetragonal-to-monoclinic transformation at the surface,² detected through Raman spectroscopy.

On the other hand, in lubricated conditions, the friction behavior is more homogeneous among the different samples, and friction coefficients are in the range of 0.18–0.20. These coefficients are in the same range of conventionally processed parts.³ Surface properties such as roughness, wettability, and porosity show a direct influence on friction mechanisms.

Regarding wear volume, alumina and zirconia present significantly higher wear volume compared to ZTA composites in both air and lubricated conditions. In air conditions, for both alumina and zirconia, a tribofilm is detected on worn surfaces. A tribofilm is a film formed on a surface because of tribology stresses that induce a chemical transformation or compact wear debris—as in this case study. Alumina tribofilm (Figure 1b) is adherent enough to resist the whole tribological test cycle (around 8 hours) and protect the surface from further wear. On the other hand, zirconia tribofilm is continuously generated and detached so the wear volume never attains a plateau and thus constantly increases.

Printed ZTA parts present an optimal tribological behavior, with a very low wear volume in both air and lubricated conditions. There is no sign of tribofilm (Figure 1d). However, the debris generated during the test “fill” the open poros-

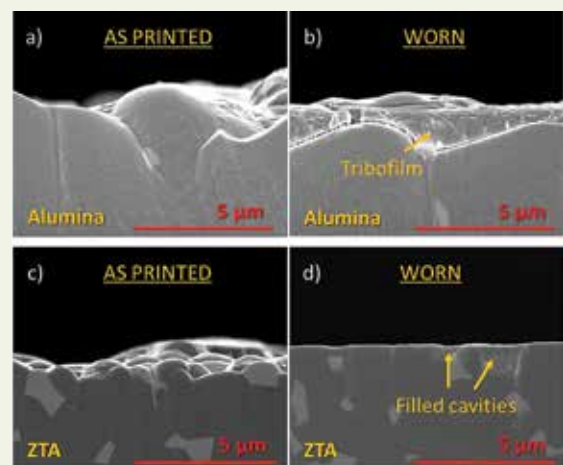


Figure 1. As printed and worn surfaces of alumina (a, b) and zirconia toughened alumina (c, d) samples.

ity on sample surface, homogenizing the surface and decreasing the roughness.

To conclude, based on both reciprocating friction coefficients and wear volume, ZTA seems to be an optimal candidate for creating additively manufactured parts for orthopedic joint implants.

References

¹Blau PJ, “Four great challenges confronting our understanding and modeling of sliding friction,” *Tribology Series* 1998; 34:117-128.

²Chevalier J, Gremillard L, Virkar A V., Clarke DR, “The tetragonal-monoclinic transformation in zirconia: Lessons learned and future trends,” *J Am Ceram Soc.* 2009; 92(9):1901–1920.

³Gispert MP, Serro AP, Colaço R, Saramago B, “Friction and wear mechanisms in hip prosthesis: Comparison of joint materials behaviour in several lubricants,” *Wear* 2006; 260(1–2):149–158.

Ambra Paterlini is a Ph.D. candidate at the University of Birmingham. Her doctoral fellowship is part of a European Marie-Curie project named DOC-3D Printing, which is focused on additive manufacturing of ceramics for medical and aeronautical applications. In addition to research, 3D printing is also a personal hobby of hers, along with outdoor activities such as camping and hiking. 100

Ceramic & Glass

DECEMBER 2021 • VOLUME 2 • ISSUE 4

MANUFACTURING

www.ceramics.org/ceramicandglassmanufacturing



WHAT'S NEXT AFTER A RECORD-SETTING YEAR FOR MERGERS AND ACQUISITIONS?

ELCON-UC DAVIS PARTNERSHIP
INVESTIGATES DISCOLORATION OF
HIGH-CALCIA ALUMINA

OPTICAL GLASS: ADVANCED ROTARY
SURFACE GRINDERS DELIVER MORE
POSSIBILITIES AND TIGHTER TOLERANCES



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The Inamori School of Engineering at Alfred University invites applications for three faculty appointments in Ceramic Engineering, one appointment in Glass Science and Engineering, and one assistant professor position in Mechanical Engineering.

Candidates must hold a PhD in Material Science and Engineering, Ceramic Engineering, Glass Science, Mechanical Engineering or closely related field. Successful candidates will be expected to develop a strong externally funded research program and a high-quality teaching portfolio.

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Candidates with expertise in the fields of ceramic processing, characterization of oxide materials, high-temperature and/or hypersonics materials, ceramic biomaterials, computational materials science, and advanced ceramic manufacturing.

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Mechanical Engineering Position:

Candidates with expertise in the broad fields of mechanical properties of materials, mechatronics, robotics, bio-mechanics, fluid mechanics, and surface and interface science.

Please contact the following with interest and questions:

Dr. Gabrielle Gaustad

Dean, Inamori School of Engineering
P 607-871-2953 E gaustad@alfred.edu
go.alfred.edu/engineering

Review of applications will begin immediately with start dates in either January or August of 2022.



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OUTSIDE of ORDINARY

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INDUSTRY NEWS



The Cornell Center for Materials Research.

CORNELL, NORTH CAROLINA A&T PARTNER TO IMPROVE DIVERSITY IN ENGINEERING

The Cornell University Center for Materials Research and North Carolina Agricultural and Technical State University began a research collaboration to increase diversity in the materials science field. North Carolina A&T said the college produces more Black engineers than any other university in the United States. Its students will visit Cornell for its state-of-the-art instrumentation and to work with Cornell faculty in electron microscopy, optics, and electrocatalysis. The National Science Foundation funded the project with a three-year, \$800,000 seed grant.

ITALIAN GLASS MAKER BUYS A COMPETITOR IN CHINA

Italian technical glass manufacturer Vetrerie Riunite has acquired 70% of the capital of Suizhong Minghui Industrial Technology, a China-based manufacturer of washing machine portholes. Vetrerie Riunite manufactures technical glass for household appliances. The integration of the Chinese company will allow Vetrerie Riunite to improve its market share from 40% to more than 50%.



Vetrerie Riunite manufactures technical glass for household appliances.



Corning invests strategically to support broadband network buildouts.

CORNING TO EXPAND ITS OPTICAL CABLE MANUFACTURING

Corning Inc. announced it is expanding its longtime collaboration with AT&T. The two companies will extend their investments in fiber infrastructure, expand U.S. broadband networks, and accelerate 5G deployment. Corning said it will invest \$150 million in optical cable manufacturing in North Carolina, initially adding 200 jobs. AT&T previously announced plans to significantly expand its fiber footprint.

SCHOTT TO INCREASE CAPACITY AT PHARMA GLASS PLANT IN INDIA

SCHOTT will invest 70 million euro to expand its pharmaceutical glass tubing site in Jambusar, Gujarat, India. The expansion will increase its production capacity in India by more than 30%. It is part of a more than \$1 billion investment program through 2025, leveraging the company's pharma tubing and packaging business.



SCHOTT's expansion supports the Indian government's vision to become a global pharmaceutical hub.



O-I to invest in high-growth markets in Latin America, the U.S., and the U.K.

O-I GLASS PLANS TO INVEST \$680 MILLION IN PLANT EXPANSIONS

O-I Glass announced plans to invest up to \$680 million globally to expand its glass packaging capacity. The Perrysburg, Ohio-based company plans to add up to 700,000 tons of glass packaging capacity by adding up to 11 lines of its Modular Advanced Glass Manufacturing Asset (MAGMA) production process. The investment will include \$100 million to expand one of the company's facilities in Colombia, and up to \$580 million in targeted markets.

HARBISONWALKER SCOUTING SITES FOR A NEW PLANT

HarbisonWalker International, the largest supplier of refractory products and services in North America, plans to build a manufacturing and service hub for steel customers in the U.S. and substantially increase production of steelmaking products. The facility, which is expected to open as early as the third quarter of 2022, will produce refractories designed for use in low emission electric arc furnaces. The company is assessing site options.



Pittsburgh-based HWI has 18 manufacturing plants and 20 global sourcing centers around the world.



Nobel laureate Novoselov, far left, and National University of Singapore officials announced the launch of a new institute.

MATERIALS SCIENCE RESEARCH CENTER INAUGURATED IN SINGAPORE

The National University of Singapore (NUS) launched an institute dedicated to the design, synthesis, and application of functional intelligent materials. Co-directed by Nobel-Prize-winning materials scientist Konstantin Novoselov, it will be the sixth research center of excellence in Singapore, and the fourth hosted at NUS. The institute is supported by the Singapore Ministry of Education, which is providing funding of S\$100 million (roughly US\$74 million) and a matching contribution of S\$100 million from the university.

HERAEUS GROUP PLANS TO ACQUIRE MO-SCI CORP.

Heraeus Group, a family-owned portfolio company based in Germany, announced its acquisition of Mo-Sci Corp., a supplier of medical and specialty glass, and ETS Technology Holdings, a provider of innovative wound care technologies. Both Mo-Sci and ETS are located in Rolla, Mo. Mo-Sci was founded by Delbert Day in 1985, and was led by Ted Day, his son, until his passing in September 2020. Heraeus said it plans to keep the existing Mo-Sci team and facilities in Rolla. Heraeus employs 14,800 people in 40 countries.



Mo-Sci supplies the medical device industry as well as the aerospace, automotive, and electronics industries.

WHAT'S NEXT AFTER A RECORD-SETTING YEAR FOR MERGERS AND ACQUISITIONS?

By David Holthaus

We're at the close of one of the most active years in merger and acquisition activity in recent memory, as several factors converged to make it a record-setting year for deals.

Low interest rates, a rising stock market, and the availability of capital all contributed to the hot market of 2021, says David Ruf, head of the chemicals and materials investment banking practice at KeyBanc Capital Markets. The biggest factor was COVID-disrupted 2020, he says. The deep uncertainty caused by the global pandemic led to business being put on hold.

"People were saying, 'I don't know if the sky is falling,' or 'I don't know if we still have a world to continue to live in,'" he says. "If I buy something in May 2020, does the world even exist by August?"

Ruf's practice generally focuses on deals under \$2 billion. Heading into 2021, deal activity that had been suppressed due to the pandemic uncertainty opened up as the economy recovered and again showed signs of stability.

"A lot of things that were scheduled to be sold in 2020 never got sold or didn't come to the market in the first place," he says. "As a result, everything that wasn't nailed down and everything that wasn't for sale or didn't come to the market in 2020 was suddenly hitting the market in the second quarter of 2021."

Pitchbook Data, the Seattle-based company that researches the venture capital, private equity, and merger and acquisition markets, reported that dealmaking through the third quarter of 2021 already broke 2019's record for annual deal value, at more than \$787 billion.

"The U.S. private equity industry is storming through 2021, smashing records as investors take advantage of a bullish climate, and remain undeterred by the possibility of inflation and interest rate hikes," the company wrote in an October analysis.

James Bauerle is a cofounder of Renaissance Partners, a Pittsburgh-based investment banking and business advisory firm. His firm's focus is on middle-market firms—ranging from a few million in sales to

\$500 million—and on the lower middle market—ranging from \$1 million to \$150 million. He recently assisted in the sale of the Paul Wissmach Glass Co., a 117-year-old family-owned business based in West Virginia.

He also has witnessed the frothy market for dealmaking. "It's an excellent time to be a seller if you have a good operating business. The multiples that people are paying are as good as they've been in my career of 40 years," he says.



Austria-based Stoezle Glass Group purchased a Monaca, Pa. glass factory from the Oneida Group's Anchor Hocking Glass Co. in August 2021. Credit: Anchor Hocking Glass Co.

In the life cycle of nearly every business there comes a time when the owners reach a crossroads that may demand fundamental decisions: Do we expand or stay the course? Is it time to buy or time to sell? Who's next in line to run the business?

These questions not only need to address the state of the business but also need to be answered in the context of the marketplace, the economy, and the prospects for the future.

Deciding whether and when to sell or buy should be an ongoing topic among business management, Bauerle says.

"People who have companies should be thinking proactively about what their strategy is and whether they should be buying, selling, expanding, or not expanding," he says. "That should be a constant top-of-mind point."

There are many reasons buyers may be looking around. One is to enter new markets, as acquiring can be a quick way to do that if the business to be purchased has built a reliable customer base.

In August, Austria-based Stoelzle Glass Group announced it had purchased a glass factory in Pennsylvania from Anchor Hocking Glass Co. for an undisclosed amount. It is Stoelzle's first glass plant in the U.S., and its first outside of Europe. The acquisition, along with further investment and modernization, will promote the company's goal of "becoming the leading supplier for high-quality glass containers in the United States and North America," the company says in a news release.

Berlin Packaging, the Milan, Italy-based supplier of glass packaging, has expanded around the world through acquisition. In August, it announced the purchase of The Juvasa Group, a family-owned packaging firm based in Spain. The acquisition "continues our efforts to expand our presence in Europe, the Middle East, and Africa," says Bill Hayes, Berlin Packaging's global CEO and president, in a press release.

It was Berlin's sixth acquisition in the Europe, Middle East, and Africa region in 2021 alone, and its sixteenth since 2016.

In February, the company announced the acquisition of Sodis-Uhart, a family-owned glass packaging concern in southern France. It was the company's eleventh acquisition in Europe since 2016.

"Expanding our presence in Europe remains a critical objective for us in 2021," Hayes said at the time. "Targeted acquisitions continue to be an important way for us to execute on our strategic growth plans for Europe."

Kyocera Corp., the global company that supplies components for the auto and electronics industries, and many others, is constantly

scanning the horizon for partnerships, some of which may eventually become acquisitions. "Kyocera is absolutely interested in new technologies and new companies," says Mark Wolf, vice president of Kyocera's Fine Ceramics Group.

Kyocera prefers to work with smaller companies as suppliers or possibly in joint ventures first before considering an acquisition.

"We really like to work with companies first to get to know them before we do anything else," Wolf says. That way, company leaders can determine whether a tie-up will gel before making a bigger investment.

In January, Kyocera completed the acquisition of SLD Laser, a California-based tech company that was started in 2013 by Nobel laureate in physics Shuji Nakamura. SLD had commercialized gallium nitride-based laser light sources that can be used in the production of fine ceramics and in other applications.

"We know innovation is happening across the world," Wolf says. "People are going to come up with ideas and exploit those, and Kyocera is interested in those ideas."

Other recent Kyocera acquisitions include its purchase in 2019 of H.C. Starck Ceramics, an advanced ceramics manufacturer and sales company based in Selb, Germany. That deal gave Kyocera its first ceramic manufacturing facility in Europe, and it brought with it a new processing technology that enabled the production of high-rigidity, large, complex-shaped materials.

Later that year, Kyocera expanded its presence in Europe with the acquisition of the advanced ceramics business of Friatec GmbH, a 156-year-old business based in Mannheim, Germany.

Private equity firms are often looking to buy or invest in companies with leading-edge technology and superior products, and they have the capital to do that. "There's more than \$2 trillion of private equity that's looking for a home and

good deals," Bauerle says.

Artemis Capital Partners, a Boston-based private equity firm, bought Superior Technical Ceramics in 2018, citing STC's technical advantages in materials and processes, its engineering expertise, and its customer-centric culture, "the hallmarks of scalable growth," the firm said when it announced the deal. Vermont-based STC was founded in 1898 and provides advanced ceramic products used in a range of applications.

Sometimes a family-owned company will transition after a generational event. Mo-Sci Corp. was founded in 1985 by Delbert Day to



David Ruf



James Bauerle



ETS Technologies' first product, a synthetic skin substitute.
Credit: ETS Technologies

develop and supply specialty glass and ceramic products for specific market applications. The company grew into a leading supplier to the medical device industry with glass microspheres, fibers, and powders. It also provides sealing glass and test services for the aerospace, automotive, and electronics industries.

The company was led by Ted Day, Delbert's son, until he passed away in September 2020 at the age of 59. A year later, Mo-Sci announced it would be acquired by the Heraeus Group, a large portfolio company based in Hanau, Germany. Heraeus is a global Fortune 500 company whose roots date to a family pharmacy started in the 17th century. Today, the Heraeus Group includes businesses in the environmental, electronics, health, and industrial applications sectors.

The acquisition also included ETS Technology Holdings, a company founded in 2012 to develop and commercialize a novel, borate-based bioactive glass technology platform for wound care.

"Mo-Sci and Heraeus have been in contact for many years, and prior to his passing, Ted identified Heraeus as a preferred partner to take Mo-Sci and ETS to the next stage of development," says Kimberly Day, the owner of both companies, in a press release.

With 2021 merger and acquisition activity setting records, what does that mean for 2022?

KeyBanc's Ruf expects dealmaking to continue to be robust, but perhaps drop off slightly following this year's torrid market. "I would expect a slightly lower volume of M&A [mergers and acquisitions] in Q1, just because we had everything being pushed through in 2021," he says.

He expects capital to continue to be readily available for borrowing, and interest rates to remain low.

The big question, he says, is what will happen to tax rates if a big spending package is passed by Congress. The tax rates on capital gains could go up significantly, he explains, which might make prospective sellers wait. Or conversely, it could make them jump into the market before any new rates take effect.

There are several tailwinds that could help propel a robust market in 2022, according to a September report from UBS Global Wealth Management. They are

- Low interest rates and government stimulus packages that are still working their way through the economy,
- Record levels of capital available in both the private and public markets,
- Pent-up supply and demand from both sellers and buyers,
- The feeling that the worst may be behind us as it relates to the pandemic, and
- Possibly speeding up exit planning due to uncertainty related to capital gains and corporate taxes.

"Companies that performed well over the COVID period are trading at attractive valuation levels and are in demand by buyers," says Alan Felder of UBS Investment Bank.

Companies planning to sell should review their operations and get them in shape before going out on the market, Bauerle says. "It's no different than selling your house," he says. "You want a house that people look at and say that's a house that I'd like to live in and I'll pay fair value for."

Steps to take could include reviewing senior management and making sure the right people are in the right roles, and creating a succession plan. Bauerle recommended finding an independent set of eyes to evaluate the business to determine what value could be expected in a sale, and what needs to be done to tune up the enterprise, both operationally and financially.

Ruf advises sellers to prepare well and prepare deeply because momentum matters in a deal. If the seller needs to gather information while the deal is in process, a delay could raise doubts, he says. "Invariably, everybody's going to wonder why the process slowed down, what problem is occurring," he says.

Crafting the story of the business and describing what sets it apart from others in the field is critical, he says. That includes describing the quality of the customer base, the product differentiation, intellectual property, and the speed and quality of service.

"We spend a lot of time with management in advance of doing anything in the capital markets, months and months of gathering data, refining the story, putting that into a single package that makes sense," he says.

Decades of working with small- to midsized manufacturers like the Paul Wissmach Glass Co., whose colored glass is shipped from Paden City, W.Va., to customers around the globe, has shown Bauerle what their story is: "It's people who know how to do what they do, and go about it without a lot of fanfare, and whose products are valued all over the world."

And that's something to take to the bank any day. ▀

STONY BROOK'S CENTER FOR THERMAL SPRAY RESEARCH CELEBRATES A MILESTONE

The Center for Thermal Spray Research (CTSR) at Stony Brook University (Stony Brook, N.Y.) has reached the significant milestone of 25 years.

The Center was established in 1996 when a team led by professor Herbert Herman, along with professors Christopher Berndt and Sanjay Sampath, converted a fledgling but successful academic activity in thermal spray materials processing into a major, multidisciplinary materials research program. A multiyear, \$4 million grant from the National Science Foundation Materials Research Science and Engineering Center (MRSEC) program provided the necessary support.

The team's premise was that thermal spray allows materials to be synthesized from extreme conditions with novel microstructures that allow important functionalities in engineering systems.

The research included contributions from scientists at the National Institute of Standards and Technology, who applied small-angle, X-ray and neutron scattering to study porosity and interfaces in layered materials. A parallel effort used neutrons to conduct depth profiles of residual stresses.

Working with colleagues at MIT, studying the mechanics of layered, defected materials offered new insights into the mechanical behavior of nontraditional materials systems. A partnership with the Stony Brook Geoscience Department allowed examination of the role of the high pressures generated during impact formation of metastable materials. Researchers also studied particle dynamics both during the melting and deposition phases.

NSF renewed the program for a second, five-year term to expand into new strategies including studies of liquid feedstock to synthesize novel chemistries, and applications of the process into electronic, magnetic, and sensor functions.

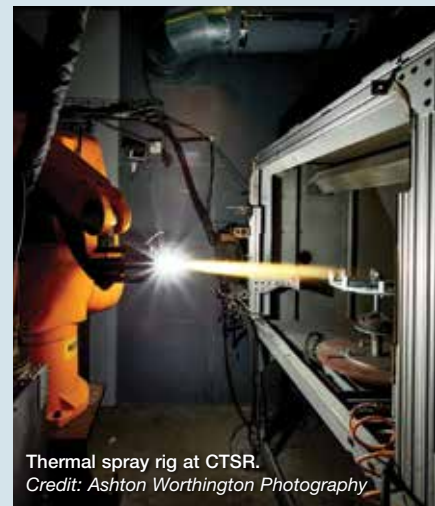
An Industrial Consortium for Thermal Spray Technology was established in 2002 with 10 companies, which allowed knowledge transfer from fundamental research to industrial practice. The Consortium continues to thrive today with 30 contributing members.



The Center's output is significant: some 50 Ph.D. students, 40 M.S. students, and 30 postdoctoral researchers were trained. Hundreds of undergraduates learned to handle complex materials processing equipment and characterization methods. More than 500 K–12 students participated in field trips. The Center's results include more than 400 refereed publications, 12 book chapters, seven patents, and three licenses.

CTSR plans a celebratory workshop in 2022 to mark this milestone, which coincides with the 20th anniversary of the Consortium partnership.

For more information, visit www.stonybrook.edu/ctsr or contact Sanjay Sampath at sanjay.sampath@stonybrook.edu or 631-632-8480. ▀



Thermal spray rig at CTSR.
Credit: Ashton Worthington Photography

ELCON–UC DAVIS PARTNERSHIP INVESTIGATES DISCOLORATION OF HIGH-CALCIA ALUMINA

By Tim Dyer and Nikki Do

As a high-tech manufacturing company that produces precision components for critical applications in several industries, Elcon Precision (San Jose, Calif.) is always investing in new technologies and developing better processes to not only meet customer specifications but also satisfy scientific curiosity.

One puzzle that Elcon has encountered for many years is discoloration of some alumina compositions during ceramic metallization, a service that Elcon offers. In this process, a proprietary thick film moly-manganese paint is applied to bare ceramic substrates to prepare them for subsequent brazing into assemblies. After metallization, parts undergo wet hydrogen firing at around 1,400°C. For aluminas with high calcia concentrations (1–2%), greyish discoloration is often observed on the surface of the ceramic (Fig. 1). This phenomenon is often called nucleation.

Although nucleation does not reduce bond strength or affect the part's physical or electrical properties, it is a cosmetic issue many customers prefer to avoid. Yet, to our knowledge, there is no published research on why this discoloration only occurs in certain aluminas and how it can be prevented.

In the spring of 2021, Elcon had the opportunity to investigate this question when a team of undergraduate students at the University of California, Davis, reached out to Elcon to collaborate on a project. Rebecca Salcedo, Elcon's process engineer, and Tim Dyer, Elcon's president, agreed to support a project with six students from professor Subhash Risbud's EMS 188 course: Rachel Altovar, Clayton Braga, Miranda Bell, Nicole Shuman, Ethan Suwandi, and Jiaying Li.

The students were excited to explore the question of nucleation and discoloration in high calcia alumina. As Shuman explains, "although our courses discussed topics such as viscosity and brittleness, there weren't any courses where we focused on ceramics or polymers. The attraction for all of us with this project was the opportunity to broaden our knowledge and skills working with ceramics." The team took to the project enthusiastically and, with a 10-week project timeline, assigned roles best suited to their strengths—project manager, literature research, material characterization, computer modeling, and experimental design.

The team focused on 97% and 97.5% aluminas from two different manufacturers that had 1–2% calcia concentration. Commonly used in defense and electronics applications, these aluminas contain calcia because the calcia acts as an alumina flux and reduces the sintering temperature significantly by formation of a calcia-alumina eutectic, which in turn reduces firing cycle times.

At Elcon, it often takes one to two weeks to get a sample run for a research and development project because resources are reserved for production. However, that approach would not have worked if the project was to meet its deadline, so the Davis team decided to start with computational modeling.

"Modeling allows you to test things before they actually happen," Suwandi says. In the case of ceramic microstructures, which are very complicated systems, understanding the composition of the material and its reactive properties under simulated conditions can pave the way to running much faster and smoother experiments.

To develop an accurate model, the team reviewed academic papers by Klaus et al.,¹ investigating the phase formation and thermal stability of the $\text{CaO-Al}_2\text{O}_3\text{-MgO}$ system under different sintering temperatures and times. These papers showed that the ternary hexa-aluminate phases CAM I ($\text{C}_2\text{M}_2\text{A}_{14}$) and CAM II (CM_2A_8) can form at a narrow temperature range of 1,400–1,700°C. In addition, Martinez et al.² found that hibonite can form as well in calcia-containing alumina materials processed between 1,150–1,500°C. These phases function as an interlock in the alumina matrix and strengthen the bonds of compounds, enhancing the substrate's thermal and mechanical properties. This microstructure observation of an aluminate ceramic system under different sintering temperatures and times pointed the team to consider these factors as the cause of discoloration.

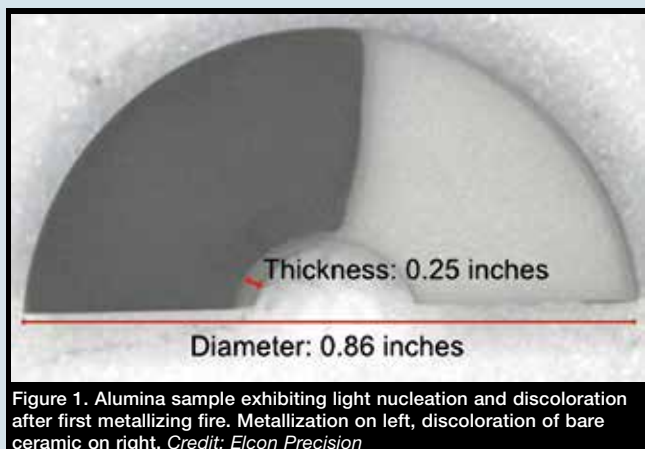


Figure 1. Alumina sample exhibiting light nucleation and discoloration after first metallizing fire. Metallization on left, discoloration of bare ceramic on right. Credit: Elcon Precision

The team used Thermo-Calc, a modeling and prediction tool commonly used in industry, in conjunction with CALPHAD (CALculation of PHase Diagrams) to produce high-resolution phase diagrams (Fig. 2). CALPHAD uses a database of experimental and theoretical values including phase compositions at equilibrium to calculate the Gibbs free energy for a specific phase. Though Thermo-Calc hosts a robust methodology and database, there is little to no experimental data available for the ternary ceramic systems being analyzed. Using Thermo-Calc Python, the team rewrote the script to add flexibility to defining the phase boundaries and necessary kinetics. Having multiple sophisticated resources and systems provided by the university allowed the team to quickly adapt to the project's needs.

Armed with this set of tools, the modeling team input compositions for the high calcia alumina samples (Al_2O_3 , SiO_2 , and CaO) into the program using the metal oxide ceramics database.³ Modeling was performed in both atmospheric (1 atm) and vacuum conditions (1×10^{-7} atm) with a temperature range of 200°C to 1,750°C to create ternary phase diagrams. Alumina samples included both discs and thin boards of 97.5% alumina (Sample A) and 97% alumina (Sample B).

Several relevant phases were identified in the high calcia alumina models, including

- **Corundum (Al_2O_3):** Dominant phase. Colorless.
- **Anorthite ($\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$):** Forms in most phase regions. White to grayish.
- **Hibonite ($\text{CaO} \cdot 6\text{Al}_2\text{O}_3$):** Forms in both samples above ~1,000°C. Brownish/black
- **Mullite ($\text{Al}_6\text{Si}_2\text{O}_{13}$):** Forms in phase regions adjacent to 97% alumina at all temperatures. Colorless, but other technical ceramic papers show a graying effect around 1,400°C.

A significant finding from these phase diagrams was that hibonite developed in the firing temperature range where the surface discoloration occurs. Hibonite is an alumina-calcia phase that is known for forming brown and grey colors between 1,150–1,500°C.² Furthermore, due to composition variations, the calcia-containing alumina samples have the disposition to form both mullite and hibonite. These findings led the team to form an early hypothesis that the discoloration was due to hibonite and/or mullite formation at temperatures above 1,000°C.

The team used these phase diagrams, the literature review, and historical production data provided by Elcon to design their experiments around this hypothesis. Designing the investigation around the phase diagrams and material compositions allowed the team to have a more directed approach while also applying their theoretical knowledge to a relevant experiment.

Suwandi says that “Within the simulation and microstructure characterization research that I do, there’s a propensity for computational

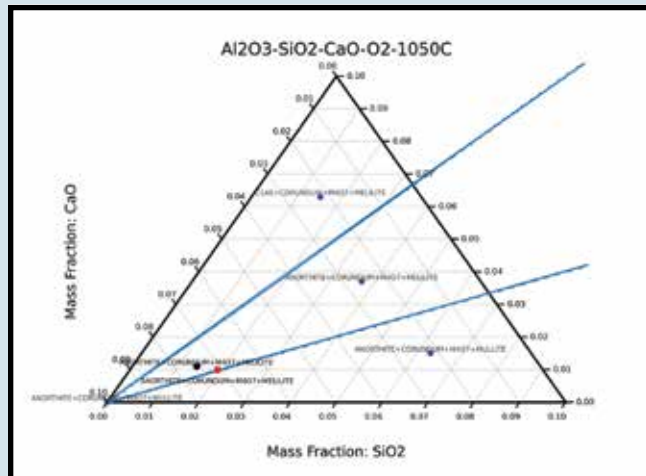


Figure 2. Phase diagram produced using Thermo-Calc for high-calcia alumina at 1,050°C and a pressure of 1 ATM (760 Torr). Credit: Elcon Precision

people to get stuck in their own world. Although you’re dealing with complex models, at the end of the day, if they’re not implemented into an experimental setting or connected to one, it kind of exists on its own. This project allowed us to apply these models to industry and pushed me onto a more specialized path, which consists of microstructure characterization and reconstruction.”

Conducted at Elcon Precision and Prairie Ceramics (San Leandro, Calif.), the experiment consisted of making adjustments in the thermal profiles, i.e., various holds under high temperatures, quenching the ceramics with rapid and slow cooling rates, and subjecting the substrates to different heat treatments. In addition, thin 99.9% pure alumina boards were painted using mixed silica and calcia glazes to serve as proxy samples to study the phase composition of the ceramic surfaces over a wide range of chemistries (Fig. 3). Lastly, there were a few trials in which the alumina disks were coated with a pure calcia wash, manipulating the surface composition.

It is important to not only understand the phases present in the ceramics, but to also understand the phase dependence and the properties of each phase. This understanding can be accomplished with tools such as X-ray diffraction (XRD) and scanning electron microscopy (SEM). Using these methods can shed light on the origins and properties of the discoloration such as phase, thermostability, and temperature dependence.

To understand the different phases present before and after metallization sintering, the alumina



Figure 3. Ring sample cross sections demonstrating nucleation-based discoloration extending far below the original surface. Credit: Elcon Precision

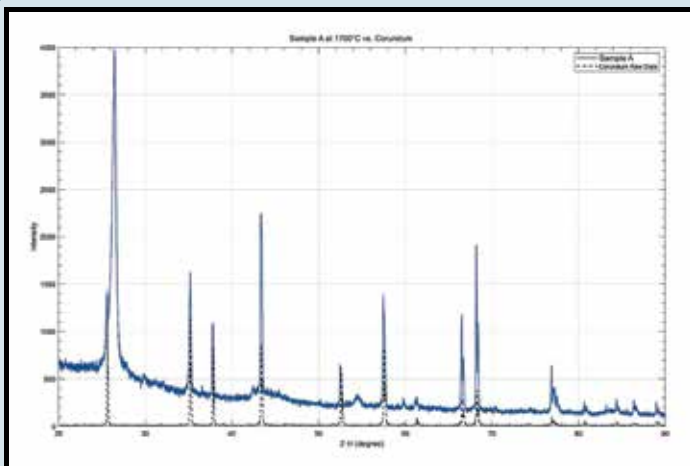


Figure 4. XRD diffraction data shown with overlapping peaks of sample A (97.5%) fired at 1,700°C with corundum. Credit: Elcon Precision

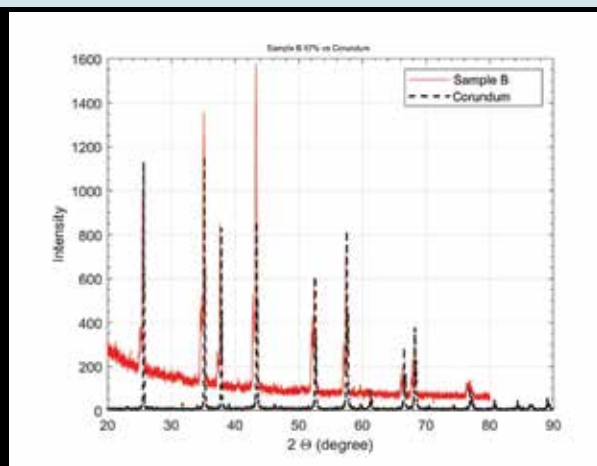


Figure 5. XRD diffraction data shown with overlapping peaks of sample B (97%) fired at 1,450°C with corundum. Credit: Elcon Precision

samples were characterized through XRD and SEM carried out in the Advanced Materials Characterization and Testing Laboratory at UC Davis. The unmetallized ceramic contains four major ternary compounds: gehlenite ($\text{Ca}_2\text{Al}_2\text{SiO}_7$), anorthite ($\text{CaAl}_2\text{Si}_2\text{O}_8$), clinopyroxene ($\text{CaAl}_2\text{SiO}_6$), and grossular ($\text{Ca}_3\text{Al}_2\text{Si}_3\text{O}_{12}$).⁴

The diffraction patterns of the alumina samples generated by XRD were compared with the expected phase's diffraction patterns to determine the phases existing in the samples. Diffraction patterns produced for sample A (97.5%) at 1,700°C and sample B (97%) fired at 1,450°C matched almost perfectly with that of corundum, suggesting that corundum is the major phase present (Figs. 4 and 5). Because it is a very common phase, identifying it prompts the hypothesis that a small amount of another phase is influencing the nucleation-based discoloration.

To improve XRD characterization of potential phase formation above 1,200°C, 99% alumina substrates were painted with a calcia-silica wash and then analyzed after metallization sintering. The diffraction patterns of some samples lined up closely with that of hibonite. This finding lends some support to the hypothesis that hibonite formed at specific temperatures, causing the discoloration.

SEM analysis of each alumina sample identified possible phases present on the surface. Based on these results, potential minority phases were identified—anorthite, mullite, and hibonite. These findings correlated with the phase diagrams generated from Thermo-Calc and also supports the hibonite formation hypothesis.

The team discovered that the discoloration created by metallization firing could be cleared by air sintering above 1,700°C followed by rapid cooling. A possible explanation for this solution is that hibonite is kinetically outcompeted by anorthite and corundum grain growth, possibly altering the local composition faster than hibonite can form.

Though the team accomplished the goal of exploring and disentangling the nucleation-based discoloration phenomenon, this academic–industry partnership sparked an even more significant realization. The culmination of literature reviews, computational modeling and characterization, and

practical experiments not only accelerated learning, but it is a powerful problem-solving strategy that many companies still overlook. This team showed that using skills and expertise from both universities and companies collaboratively can improve materials processing performance.

When the students were asked what they wished to see more of regarding academic–industry partnerships in the future, Braga says he would “like to see more companies branch out and use university hires.” Supporting that, Suwandi believes that “there are a lot of opportunities for small companies, especially in the materials industry,” that should leverage the fact that “our curriculum is very theoretical, so we lack industry experience.” Suwandi adds that this project gave them an “experience with an entirely different set of rules and expectations than what goes on in the research side in a lab.”

ACKNOWLEDGEMENTS

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OPTICAL GLASS: ADVANCED ROTARY SURFACE GRINDERS DELIVER MORE POSSIBILITIES AND TIGHTER TOLERANCES

By Carlo Chatman, Power PR

To combat the loss of seasoned operators to retirement, glass job shops are turning to more modern automated surface grinders.

Older flat glass grinding equipment has limited mechanical controls and can require significant expertise, as well as time and labor to accomplish a task. For instance, such machines often use large wheels and dials to control the grinder's movement, meaning that the soft touch of an expert machinist is required to run them instead of programmable machine controls.

However, experienced operators who can successfully run such equipment are in increasingly short supply, and this shortage presents challenges to companies that rely on the older equipment.

"When I started almost 20 years ago, we were still using old, rotary surface grinders from the 1940s and '50s. They are tried-and-true, but not very accurate without an experienced machinist using them," says Brennan Cipro, chief engineer of Worcester, Mass.-based Howard Glass Company, which specializes in glass grinding and polishing for industries such as optics, biomedical, electronics, and aerospace.

Howard Glass focuses on 2D glass shapes, so factors such as thickness, parallelism, and surface condition are very important. Cipro notes that the glass materials provided by factories have varying degrees of standard thickness, meaning that glass materials often must be ground to smaller, precise dimensions. When using older grinding equipment, achieving such precision often requires the use of another machine to provide the final grind and polish, which adds hours to the fabrication process and contributes to inefficient production.

Modern automated rotary surface grinders offer advanced sensors and controls that can reliably achieve tighter dimensional tolerances, flatness, parallelism, and surface finish in much less time. The equipment can be used to grind flat glass to precise dimensions before polishing, significantly reducing intermediate lapping steps as well as preventing breakage of what is often a high-value product.

"The possibilities are endless with the new automated grinders," says Cipro. "Operators can enter the specific requirements, for example, 712 RPMs on the spindle, 22 RPMs on the table, with a down-feed

rate of 0.003 inches a minute, with a certain dwell cycle. Essentially, operators can program the machine to do whatever they want."

Three years ago, Howard Glass had the opportunity to purchase a used, vertical spindle rotary table surface grinder from another shop that had completed a project and no longer needed it. The IG 280 SD from Winona, Minn.-based DCM Tech, a designer and builder of industrial rotary surface grinders, has a 24-inch, variable speed table and a 20-horsepower, variable speed grinding spindle motor.

YOUR VALUABLE PARTNER IN MATERIAL SCIENCE

- Alumina
- Sapphire
- Quartz
- Boron Nitride

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Modern rotary surface grinders like those from DCM Tech offer advanced sensors and controls that can reliably achieve tighter dimensional tolerances, flatness, parallelism, and surface finish in much less time. Credit: DCM Tech

In this machine, grinding is not performed by the peripheral edge of the wheel but rather by the entire diameter of the abrasive surface. In addition, digital technology allows for an interface with easy-to-use touchscreen controls. When combined with automation, the surface grinder operators no longer need to be highly trained individuals.

"The IG 280 from DCM Tech had a digital readout, memory, and could remember where 'zero' was, so it was an important upgrade that helped with efficiency, accuracy, and surface finish," Cipro says. "It enabled us to grind the glass very close to the final dimensions, so only a tiny bit had to be removed in the polishing process, which saves tremendous time."

After a decades-old traditional surface grinder stopped working, Howard Glass decided to invest in a new IG 280, and shortly thereafter a larger format IG 380, which comes with a 36-inch, variable speed table and a 30-horsepower spindle motor. Cipro says he was immediately impressed with the automation and refinements made by DCM since the early version of the IG 280.

One example of innovation involves the automation of the initial contact between the wheel and the part. Traditionally, this contact had to be finessed by the operator, but with the new machine, the advanced sensor technology senses vibration. In addition, it automatically fine-tunes not only the pressure of the spindle motor but also how quickly it moves the abrasive wheel down onto the part.

When the machine senses the abrasive wheel has contacted the part, it automatically begins the grind cycle, which helps to minimize the potential breakage of sensitive glass or crystal parts. This capability is important in loud manufacturing facilities where operators cannot rely on listening for the sound of initial contact between the abrasive wheel and the part. Given that many such parts are high value, an operator coming in too aggressively and breaking a part can cost the company hundreds or thousands of dollars.

"I was amazed at the refinements and tighter tolerances now possible," Cipro says. "Previously, when precision down to ten-thousandths of an inch was required, it could take three hours to remove the excess on our interim machine. Now, we can grind down to ten-thousandths of an inch quickly and effortlessly without extra steps."



DCM Tech automated rotary surface grinders can be used to grind flat glass to precise dimensions before polishing, significantly reducing intermediate lapping steps as well as preventing breakage of what is often a high-value product. Above, glass discs before and after grinding. Credit: DCM Tech

In addition to reducing the needed number of finishing steps, the process repeatably achieves high throughput and eliminates variability, which enables job shops to achieve high-quality final parts, batch after batch.

Making parts in less time does no one any good if half of the parts do not pass the final inspection and cannot be used. So, the more job shops can optimize the upfront glass grinding process, the less polish time is required, thus improving not only the cycle time but also lowering costs and increasing revenue.

Perhaps even more important to Howard Glass were improvements in flexible processing that allow operators to enter virtually any requirement into a touch screen with programmable human machine interface controls. Cipro adds that, with this kind of flexibility, if a piece of glass breaks, it is easy to back any factor down a little to prevent the issue from reoccurring.

He points out that for routine processes, the use of different grind "recipes," with sets of parameters for specific parts, can further speed production, enhance quality, and aid in quick changeover.

"If the glass is a little off in the first pass, the DCM grinder can be programmed to take corrective actions on subsequent passes. There is no need to pick up the glass and measure it after every move, as with older machines," he says.

As the tolerances for glass and crystal grinding become stricter and production requirements more demanding, job shops that take advantage of advanced, automated rotary surface grinders will stay competitive even as experienced operators retire.

"Every day I hear my operators discussing ways to improve our glass grinding process because of the versatility of the advanced equipment. We are still discovering its potential," concludes Cipro.

For more information, visit www.dcm-tech.com or send an email to info@dcm-tech.com.

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Calendar of events

December 2021

1–4 ICAPMA-JMAG (Joint International Conference on Applied Physics and Materials Applications & Applied Magnetism and Ferroelectrics) – Nongnooch Pattaya International Convention and Exhibition Center (NICE), Pattaya, Thailand; <https://www.matscitech-thailand.com/2021/index.php>



12–17 14th Pacific Rim Conference on Ceramic and Glass Technology (PACRIM 14) including Glass & Optical Materials Division 2021 Annual Meeting (GOMD 2021) – VIRTUAL EVENT ONLY; <https://ceramics.org/pacrim14>



13–14 85th Annual Session of the Indian Ceramic Society presents Advances in Ceramics & Cement Technologies: Materials & Manufacturing – VIRTUAL EVENT ONLY; <http://www.icskc.in>

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> – HYBRID EVENT



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> – HYBRID EVENT

March 2022

9–10 Sustainable Industrial Manufacturing (SIM) – Brussels, Belgium; <https://sustainableindustrialmanufacturing.com/europe>

15–18 17th Biennial Worldwide Congress Unified International Technical Conference on Refractories – Hilton Chicago, Chicago, Ill.; <https://ceramics.org/unitecr2021>

May 2022

9–12 ACerS 2022 Structural Clay Products Division & Southwest Section Meeting in conjunction with the National Brick Research Center Meeting – Omni Charlotte Hotel, Charlotte, N.C.; <https://ceramics.org/scpd2022>



22–26 Glass & Optical Materials Division Annual Meeting (GOMD 2022) – Hyatt Regency Baltimore, Baltimore, Md.; <https://ceramics.org/gomd2022>

June 2022

13–15 12th Advances in Cement-Based Materials (Cements 2022) – University of California, Irvine; <https://ceramics.org/cements2022>

21–22 ceramitec 2022 – Munich, Germany; <https://www.ceramitec.com/en/trade-fair/information/exhibition-sectors>

July 2022



3–8 ➔ ICG Annual Meeting 2022 – Berlin, Germany; <https://ceramics.org/event/icg-annual-meeting-2022>

10–14 International Congress on Ceramics (ICC9) – Krakow, Poland; <https://ceramics.org/event/international-congress-on-ceramics-icc9>

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

October 2022



14–19 ACerS 124th Annual Meeting with Materials Science & Technology 2022 – David L. Lawrence Convention Center, Pittsburgh, Pa.; <https://ceramics.org/event/acers-124th-annual-meeting-with-materials-science-technology-2022>

August 2023

NEW DATE

27–31 The International Conference on Sintering 2023 (Sintering 2023) – Nagaragawa Convention Center, Gifu, Japan; <https://www.sintering2021.org>

July 2024

14–19 International Congress on Ceramics – Hotel Bonaventure, Montreal, Canada; www.ceramics.org

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

Entries in **BLUE** denote ACerS events.

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denotes International Year of Glass event



denotes virtual meeting

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In this issue (pages 39 to 54)

Look for more business-to-business news in 2022:

- April
- June/July
- September
- December

Need more information on how to reach this audience? Call Mona Thiel at 614-794-5834 or email mthiel@ceramics.org

Statement of Ownership

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A. Total number of copies (net press run)	6,959	8,011
B. Paid and/or requested circulation		
1. Paid/requested outside-county mail subscriptions	2,845	2,890
2. Paid in-county subscriptions	none	none
3. Sales through dealers and carriers, street vendors, counter sales and other non-USPS paid distribution	1,595	1,723
4. Other classes mailed through the USPS	none	none
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1. Outside-county	2,220	3,014
2. In-county	none	none
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4. Free or Nominal Rate Distribution Outside the Mail (Carriers or other means)	127	286
E. Total Free or Nominal Rate Distribution	2,347	3,300
F. Total distribution	6,787	7,913
G. Copies not distributed	57	38
H. Total	6,844	7,951
I. Percent paid and/or requested circulation	65.42%	58.30%

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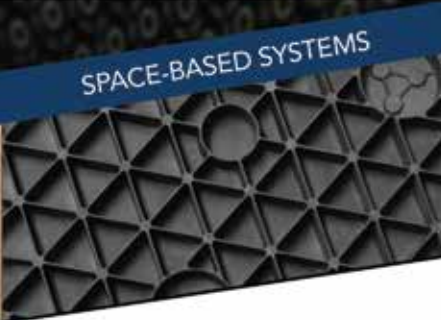
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Lithoz GmbH NY
Momentive Performance Materials Inc NY
Morgan Technical Ceramics Auburn CA

Mo-Sci Corp MO

See ad on page 95

NEVZ-Ceramics Close JSC Russia
nGimat LLC KY
NGK Spark Plug Co Ltd Japan
NovaBone Products LLC FL
O'Keefe Ceramics Inc CO
Precision Ferrites and Ceramics Inc CA
Refractron Technologies Corp NY
Robocasting Enterprises LLC NM
Tethon 3D NE

Trans-Tech Inc a subsidiary of Skyworks Solutions Inc MD

See ad on page 81

Z-Systems USA Inc MA

Boride Products

Advanced Ceramics Manufacturing AZ
Advanced Materials Associates CO
Beijing Cerametek Materials Co Ltd China
Dunhua Zhengxing Abrasive Co Ltd China
Momentive Performance Materials Inc NY
North American Hoganas PA
Refrac Systems AZ
Saint-Gobain Performance Ceramics & Refractories & Hexoloy SiC Materials MA
Treibacher Industrie AG Austria

Carbide Products

Advanced Ceramics Manufacturing AZ
Advanced Materials Associates CO
Beijing Cerametek Materials Co Ltd China
Cancarb Limited Canada
CoorsTek CO
Custom Processing Services PA
Denka Corp NY
Dunhua Zhengxing Abrasive Co Ltd China
FELDCO Intl CA
Ferro Ceramic Grinding Inc MA
Ferrotec Ceramic Products China
Free Form Fibers NY
Inducerceramic Canada
Momentive Performance Materials Inc NY
Morgan Technical Ceramics Auburn CA
MSE Supplies AZ
NGK Spark Plug Co Ltd Japan
North American Hoganas PA
O'Keefe Ceramics Inc CO
Ortech Inc CA
Polymer Innovations Inc CA
Precision Ceramics FL
Precision Ferrites and Ceramics Inc CA
PremaTech Advanced Ceramics MA
Refrac Systems AZ
Saint-Gobain Ceramics & Plastics MA
Silicon Carbide Products Inc NY
Superior Graphite Co IL
Toto Ltd Japan
Treibacher Industrie AG Austria
Zhengzhou Mission Ceramic Products Co Ltd China

Catalysts

Arkema Inc PA
Blasch Precision Ceramics Inc NY
CARBO Texas
CerPoTech AS Norway
Haldor Topsøe A/S Denmark
Inducerceramic Canada
Johnson Matthey Technology Centre UK
MemPro Materials Corp
Momentive Performance Materials Inc NY
Nexceris LLC OH
P-Ker Engineering NY
Robocasting Enterprises LLC NM
Saint-Gobain NorPro OH
Zibo Guangtong Chemical Co Ltd China

Cermets

AdTech Ceramics TN
Advanced Materials Associates CO
CeramTec North America Corp SC
CoorsTek CO
Innovnano - Advanced Materials SA Portugal

Coatings

Advanced Materials Associates CO
Aremco Products Inc NY
Arkema Inc PA
Bharat Heavy Electricals Ltd India
Cerakote Ceramic Coatings OR

Cerion Nanomaterials NY
CerPoTech AS Norway
CoorsTek CO
Hexion Inc OH
II-VI Aerospace & Defense CA
Jyoti Ceramic Industries Pvt Ltd India
Master Bond Inc NJ
Morgan Advanced Materials CA
Nanofilm OH
New Tech Ceramics Inc IA
Nexceris LLC OH
P-Ker Engineering NY
Polymer Innovations Inc CA
Saint-Gobain Ceramics & Plastics MA
Sigma Advanced Materials NY
Technology Assessment and Transfer Inc (TA&T) MD
Teeter Marketing Services LLC FL

See ad on page 61

TevTech LLC MA

See ad on page 89

Trans-Tech Inc a subsidiary of Skyworks Solutions Inc MD

See Ad on Page 81

Zibo Guangtong Chemical Co Ltd China
ZYP Coatings Inc TN

Composites, Carbon-Carbon

Advanced Materials Associates CO
Cancarb Limited Canada
Refrac Systems AZ
Starfire Systems Inc NY

Composites, Ceramic-Ceramic

Advanced Ceramics Manufacturing AZ
Advanced Materials Associates CO
Bharat Heavy Electricals Ltd India
Bullen OH
CerPoTech AS Norway
Elan Technology GA
FCT Ingenieurkeramik GmbH Germany
Ferro Ceramic Grinding Inc MA
Free Form Fibers NY
Morgan Technical Ceramics Auburn CA
NEVZ-Ceramics Close JSC Russia
New Tech Ceramics Inc IA
O'Keefe Ceramics Inc CO
PremaTech Advanced Ceramics MA
Refrac Systems AZ
Silicon Carbide Products Inc NY
Starfire Systems Inc NY
Technology Assessment and Transfer Inc (TA&T) MD
Viridis3D LLC MA
Zhengzhou Mission Ceramic Products Co Ltd China

Composites, Ceramic-Metal

AdTech Ceramics TN
Advanced Materials Associates CO
Diamorph AB UK
Elan Technology GA
Free Form Fibers NY
Hunter Chemical LLC PA
Innovnano - Advanced Materials SA Portugal
NEVZ-Ceramics Close JSC Russia
New Tech Ceramics Inc IA
Precision Ceramics FL
Precision Ferrites and Ceramics Inc CA
Refrac Systems AZ
Sigma Advanced Materials NY
Starfire Systems Inc NY
Technology Assessment and Transfer Inc (TA&T) MD
Viridis3D LLC MA
Zibo Guangtong Chemical Co Ltd China

Composites, Ceramic-Polymer

Advanced Materials Associates CO
Bullen OH
Cerakote Ceramic Coatings OR

NovaBone Products LLC FL
O'Keefe Ceramics Inc CO
Polymer Innovations Inc CA
Starfire Systems Inc NY
Verity Technical Consultants LLC OH
Viridis3D LLC MA

Composites, Intermetallic

FELDCO Intl CA
Zibo Guangtong Chemical Co Ltd China

Cutting Tools

Advanced Ceramics Manufacturing AZ
Advanced Materials Associates CO
Astro Met Advanced Ceramics Inc OH
Cerakote Ceramic Coatings OR
CeramTec North America Corp SC
CoorsTek CO
Dianamic Abrasive Products Inc MI
Ferro Ceramic Grinding Inc MA
New Tech Ceramics Inc IA
NGK Spark Plug Co Ltd Japan
PremaTech Advanced Ceramics MA
Rauschert Industries Inc GA
RocCera LLC NY
Thermocarbon FL
Xiamen Unipretec Ceramic Technology Co Ltd China
Zibo Guangtong Chemical Co Ltd China

Cylinders

Advanced Ceramics Manufacturing AZ
Cerakote Ceramic Coatings OR
CoorsTekCO
Ferrotec Ceramic Products China
Morgan Technical Ceramics Auburn CA
Suntech Advanced Ceramics (Shenzhen) Co Ltd China

Dies

Astro Met Advanced Ceramics Inc OH
North Star Equipment Inc WA
Petro Mold Company PA
Ram Products Inc OH
Refractron Technologies Corp NY
Xiamen Unipretec Ceramic Technology Co Ltd China
Zircoa Inc OH

Engine Components

Advanced Ceramic Technology CA
Advanced Ceramics Manufacturing AZ
Cerakote Ceramic Coatings OR
CeramTec North America Corp SC
Elcon Precision LLC CA
Federal-Mogul MI
Ferro Ceramic Grinding Inc MA
Ferrotec Ceramic Products China
GE Global Research NY
Precision Ceramics FL
PremaTech Advanced Ceramics MA
Toyota Central R&D Labs Inc Japan
Xiamen Unipretec Ceramic Technology Co Ltd China

Filters

Akron Porcelain & Plastics Co OH
Bharat Heavy Electricals Ltd India
Blasch Precision Ceramics Inc NY
Inducerceramic Canada
Maryland Ceramic & Steatite Co Inc MD
Rauschert Industries Inc GA
Refractron Technologies Corp NY
Robocasting Enterprises LLC NM
Starfire Systems Inc NY
Valley Design Corp MA
Zhengzhou Mission Ceramic Products Co Ltd China

Glass-Ceramics

Accuratus Corp NJ
Achtech Precision Ceramic (HK) Limited China
Aremco Products Inc NY
Astro Met Advanced Ceramics Inc OH
Bharat Heavy Electricals Ltd India
Cerlase France
CoorsTek CO
Elan Technology GA
Ferro Ceramic Grinding Inc MA
Israel Ceramic & Silicate Inst Israel
Keeling & Walker Ltd UK
Morgan Advanced Materials CA
Ortech Inc CA
Petro Mold Company PA
P-Ker Engineering NY
Precision Ceramics FL
PremaTech Advanced Ceramics MA
RISE Research Institutes of Sweden RISE Glass Sweden
Schott North America Inc NY
Starfire Systems Inc NY
Technical Products Inc WI
TevTech LLC MA See ad on page 89
Valley Design Corp MA
Xiamen Unipretec Ceramic Technology Co Ltd China
Zibo Guangtong Chemical Co Ltd China

Heat Exchangers

Arkema Inc PA
Blasch Precision Ceramics Inc NY
Dowa High Temp Furnaces India
Elcon Precision LLC CA
FCT Ingenieurkeramik GmbH Germany
Ferrotec Ceramic Products China
Inducerceramic Canada
Precision Ceramics FL
Refrac Systems AZ
Saint-Gobain Performance Ceramics & Refractories &
Hexoloy SiC Materials MA

Honeycombs

Bharat Heavy Electricals Ltd India
Blasch Precision Ceramics Inc NY
Inducerceramic Canada
Rauschert Industries Inc GA
Robocasting Enterprises LLC NM
Zhengzhou Mission Ceramic Products Co Ltd China

Industrial Parts

Accuratus Corp NJ
Advanced Ceramic Technology CA
Advanced Ceramics Manufacturing AZ
Akron Porcelain & Plastics Co OH
Astral Material Industrial Co Ltd China
Astro Met Advanced Ceramics Inc OH
Bharat Heavy Electricals Ltd India
Blasch Precision Ceramics Inc NY
Ceramco Inc NH
CeramTec North America Corp SC
CeramTec-ETEC Germany
CerCo LLC OH
Dowa High Temp Furnaces India
Du-Co Ceramics Company PA
Elcon Precision LLC CA
EZG Manufacturing Inc OH
FCT Ingenieurkeramik GmbH Germany
Ferro Ceramic Grinding Inc MA
Ferrotec Ceramic Products China
GE Global Research NY
Inducerceramic Canada
Industrial Ceramic Products Inc OH
Jyoti Ceramic Industries Pvt Ltd India
McDaniel Advanced Ceramic Technologies LLC PA
Morgan Advanced Materials CA
Morgan Technical Ceramics Auburn CA

NGK Spark Plug Co Ltd Japan
Precision Ceramics FL
PremaTech Advanced Ceramics MA
Rauschert Industries Inc GA
Silicon Carbide Products Inc NY
Sonya Ceramics (Export Division) India
Xiamen Unipretec Ceramic Technology Co Ltd China
Zhengzhou Mission Ceramic Products Co Ltd China

Injection-Molded Ceramics

Achtech Precision Ceramic (HK) Limited China
AdTech Ceramics TN
Bharat Heavy Electricals Ltd India
Blasch Precision Ceramics Inc NY
Ceramco Inc NH
CerCo LLC OH
CerPoTech AS Norway
Diamorph AB UK
Indo US MIM Tec India
Ortech Inc CA
Rauschert Industries Inc GA
Starfire Systems Inc NY
Suntech Advanced Ceramics (Shenzhen) Co Ltd China
Xiamen Unipretec Ceramic Technology Co Ltd China

Lasers, Ceramic

Accuratus Corp NJ
Achtech Precision Ceramic (HK) Limited China
CeraNova Corp MA
Cerinnov France
Cerlase France
CerPoTech AS Norway



II-VI Aerospace & Defense CA See ad on page 61

Israel Ceramic & Silicate Inst Israel
Morgan Technical Ceramics Auburn CA
nGimat LLC KY
Precision Ceramics FL
Technology Assessment and Transfer Inc (TA&T) MD

Magnesium & Compounds

Elcon Precision LLC CA

Membranes, Ceramic

Bharat Heavy Electricals Ltd India
Cerlase France
CerPoTech AS Norway
Inducerceramic Canada
NorECs AS Norway
Rauschert Industries Inc GA
Refractron Technologies Corp NY

Nitride Products

Accuratus Corp NJ
AdTech Ceramics TN
Advanced Ceramic Technology CA
Advanced Ceramics Manufacturing AZ
Beijing Cerametek Materials Co Ltd China
Blasch Precision Ceramics Inc NY
FCT Ingenieurkeramik GmbH Germany
Ferro Ceramic Grinding Inc MA
Inducerceramic Canada
Momentive Performance Materials Inc NY
NEVZ-Ceramics Close JSC Russia
NGK Spark Plug Co Ltd Japan
North American Hogan PA

O'Keefe Ceramics Inc CO
Precision Ceramics FL
Precision Ferrites and Ceramics Inc CA
Saint-Gobain Ceramics & Plastics MA
Saint-Gobain Performance Ceramics & Refractories & Hexoloy SiC Materials MA
Silicon Carbide Products Inc NY
Treibacher Industrie AG Austria
Zhengzhou Mission Ceramic Products Co Ltd China

Nuclear Waste Containers

Precision Ferrites and Ceramics Inc CA

Optical Ceramics

CeraNova Corp MA
Elcon Precision LLC CA
FELDCO Intl CA
Innovnano - Advanced Materials SA Portugal
Morgan Technical Ceramics Auburn CA
MSE Supplies AZ
nGimat LLC KY
PramaTech Advanced Ceramics MA
Suntech Advanced Ceramics (Shenzhen) Co Ltd China
Surmet Corp MA
Technology Assessment and Transfer Inc (TA&T) MD
Toto Ltd Japan

Oxide Products

Accuratus Corp NJ
Arlimin Industries CO
Associated Ceramics & Technology Inc PA
Astro Met Advanced Ceramics Inc OH
Beijing Cerametek Materials Co Ltd China
Blasch Precision Ceramics Inc NY
Ceramco Inc NH
CeramTec North America Corp SC
CeramTec-ETEC Germany
CerPoTech AS Norway
Du-Co Ceramics Company PA
FELDCO Intl CA
Ferro Ceramic Grinding Inc MA
Hunter Chemical LLC PA
Imerys Fused Minerals Murg GmbH Germany
Innovnano - Advanced Materials SA Portugal
Jyoti Ceramic Industries Pvt Ltd India
Keeling & Walker Ltd UK
MSE Supplies AZ
Nanocerox UT
nGimat LLC KY
Nyacol Nano Technologies Inc MA
Polymer Innovations Inc CA
Rauschert Industries Inc GA
Refractron Technologies Corp NY
Robocasting Enterprises LLC NM
Superior Technical Ceramics CorpVT
Trans-Tech Inc a subsidiary of Skyworks Solutions Inc MD See ad on page 81

Porous Ceramics

Associated Ceramics & Technology Inc PA
Bharat Heavy Electricals Ltd India
Ceramco Inc NH
P-Ker Engineering NY
Polymer Innovations Inc CA
Robocasting Enterprises LLC NM
Technology Assessment and Transfer Inc (TA&T) MD
Tethon 3D NE
Zhengzhou Mission Ceramic Products Co Ltd China
Zircar Zirconia Inc NY

Reinforcements, Fiber

Free Form Fibers NY
MemPro Materials Corp

Rings

Astro Met Advanced Ceramics Inc OH
CeramTec-ETEC Germany
CoorsTek CO
Dunhua Zhengxing Abrasive Co Ltd China
Elcon Precision LLC CA
FCT Ingenieurkeramik GmbH Germany
Ferro Ceramic Grinding Inc MA
Ferrotec Ceramic Products China
Industrial Ceramic Products Inc OH
Ipsen Ceramics IL
Morgan Technical Ceramics Auburn CA
Ortech Inc CA
Precision Ceramics FL
PramaTech Advanced Ceramics MA
Rauschert Industries Inc GA
Refractron Technologies Corp NY
Saint-Gobain NorPro OH
Saint-Gobain Performance Ceramics & Refractories & Hexoloy SiC Materials MA
Silicon Carbide Products Inc NY
Suntech Advanced Ceramics (Shenzhen) Co Ltd China
Superior Technical Ceramics Corp VT
Xiamen Unipretec Ceramic Technology Co Ltd China
Zhengzhou Mission Ceramic Products Co Ltd China

Rods

Accuratus Corp NJ
Advanced Ceramics Manufacturing AZ
Astro Met Advanced Ceramics Inc OH
CeramTec-ETEC Germany
CoorsTek CO
Du-Co Ceramics Company PA
Dunhua Zhengxing Abrasive Co Ltd China
Elcon Precision LLC CA
FCT Ingenieurkeramik GmbH Germany
Ferro Ceramic Grinding Inc MA
Ferrotec Ceramic Products China
Industrial Ceramic Products Inc OH
Morgan Technical Ceramics Auburn CA
Ortech Inc CA
Precision Ceramics FL
PramaTech Advanced Ceramics MA
Progressive Technology Inc CA
Rauschert Industries Inc GA
Saint-Gobain Performance Ceramics & Refractories & Hexoloy SiC Materials MA
Silicon Carbide Products Inc NY
Suntech Advanced Ceramics (Shenzhen) Co Ltd China
Superior Technical Ceramics CorpVT
Xiamen Unipretec Ceramic Technology Co Ltd China
Zhengzhou Mission Ceramic Products Co Ltd China

Silicide Products

Astral Material Industrial Co Ltd China
North American Hoganas PA

Silicon Carbide Products

Accuratus Corp NJ
Actech Precision Ceramic (HK) Limited China
Advanced Ceramic Technology CA
Advanced Ceramics Manufacturing AZ
Astral Material Industrial Co Ltd China
Blasch Precision Ceramics Inc NY
Cancarb Limited Canada
CoorsTek CO
Custom Processing Services PA
Diamorph AB UK
FCT Ingenieurkeramik GmbH Germany
FELDCO Intl CA
Ferrotec Ceramic Products China
Free Form Fibers NY



II-VI Aerospace & Defense CA See ad on page 61

Morgan Advanced Materials CA
O'Keefe Ceramics Inc CO
Ortech Inc CA
Precision Ceramics FL
Precision Ferrites and Ceramics Inc CA
PramaTech Advanced Ceramics MA
Rauschert Industries Inc GA
Refractron Technologies GmbH Germany
Saint-Gobain Ceramics & Plastics MA
Saint-Gobain Performance Ceramics & Refractories & Hexoloy SiC Materials MA
Silicon Carbide Products Inc NY
Starfire Systems Inc NY
Technology Assessment and Transfer Inc (TA&T) MD
TevTech LLC MA See ad on page 89
Zhengzhou Mission Ceramic Products Co Ltd China

Silicon Nitride Products

Accuratus Corp NJ

Silicon Nitride Products

Actech Precision Ceramic (HK) Limited China
Advanced Ceramic Technology CA
Advanced Ceramics Manufacturing AZ
Beijing Cerametek Materials Co Ltd China
CoorsTek CO
FELDCO Intl CA
Ferrotec Ceramic Products China
Free Form Fibers NY
Inducerceramic Canada
International Ceramic Engineering MA
Morgan Advanced Materials CA
O'Keefe Ceramics Inc CO
Precision Ceramics FL
Precision Ferrites and Ceramics Inc CA
Rauschert Industries Inc GA
Saint-Gobain Performance Ceramics & Refractories & Hexoloy SiC Materials MA
Technology Assessment and Transfer Inc (TA&T) MD
Zhengzhou Mission Ceramic Products Co Ltd China

Thickening Agents

Lubrizol Performance Coating OH Agents

Thread Guides

Akron Porcelain & Plastics Co OH
Associated Ceramics & Technology Inc PA
Astro Met Advanced Ceramics Inc OH
Ceramco Inc NH
CeramTec North America Corp SC
Industrial Ceramic Products Inc OH
International Ceramic Engineering MA
Ortech Inc CA
Rauschert Industries Inc GA
Superior Technical Ceramics Corp VT
Zhengzhou Mission Ceramic Products Co Ltd China

Transparent Ceramics

CeraNova Corp MA
CoorsTek CO
Ferrotec Ceramic Products China
Israel Ceramic & Silicate Inst Israel
nGimat LLC KY
Precision Ferrites and Ceramics Inc CA
PramaTech Advanced Ceramics MA
Surmet Corp MA

Tubes

Accuratus Corp NJ
AdValue Technology LLC AZ See ad on page 51
 Advanced Ceramics Manufacturing AZ
 Akron Porcelain & Plastics Co OH
 Aremco Products Inc NY
 Associated Ceramics & Technology Inc PA
 Astro Met Advanced Ceramics Inc OH
 Blasch Precision Ceramics Inc NY
 Ceramco Inc NH
 CeramTec North America Corp SC
 CoorsTek CO
 Du-Co Ceramics Company PA
 Dunhua Zhengxing Abrasive Co Ltd China
 EBL Products Inc CT
 Elcon Precision LLC CA
 Ferrotec Ceramic Products China
 Inducerceramic Canada
 Industrial Ceramic Products Inc OH
 International Ceramic Engineering MA
 Jyoti Ceramic Industries Pvt Ltd India
 McDanel Advanced Ceramic Technologies LLC PA
 Morgan Technical Ceramics Auburn CA
 Ortech Inc CA
 Precision Ceramics FL
 Progressive Technology Inc CA
 Rauschert Industries Inc GA
 Refractron Technologies Corp NY
 Saint-Gobain Performance Ceramics & Refractories & Hexoloy SiC Materials MA
 Silicon Carbide Products Inc NY
 Suntech Advanced Ceramics (Shenzhen) Co Ltd China
 Superior Technical Ceramics Corp VT
 Xiamen Unipretec Ceramic Technology Co Ltd China
 Zhengzhou Mission Ceramic Products Co Ltd China
 Zircoa Inc OH

Wear-Resistant Parts

Accuratus Corp NJ
AdValue Technology LLC AZ See ad on page 51
 Advanced Ceramic Technology CA
 Advanced Ceramics Manufacturing AZ
 Akron Porcelain & Plastics Co OH
 Associated Ceramics & Technology Inc PA
 Astral Material Industrial Co Ltd China
 Astro Met Advanced Ceramics Inc OH
 Bharat Heavy Electricals Ltd India
 Blasch Precision Ceramics Inc NY
 Ceramco Inc NH
 CeramTec North America Corp SC
 CeramTec-ETEC Germany
 CerCo LLC OH
 CoorsTek CO
 Diamorph AB UK
 EBL Products Inc CT
 FCT Ingenieurkeramik GmbH Germany
 FELDCO Intl CA
 Ferro Ceramic Grinding Inc MA
 Ferrotec Ceramic Products China
 Ipsen Ceramics IL
 Jyoti Ceramic Industries Pvt Ltd India
 McDanel Advanced Ceramic Technologies LLC PA
 Morgan Advanced Materials CA
 Morgan Technical Ceramics Auburn CA
 NEVZ-Ceramics Close JSC Russia
 New Tech Ceramics Inc IA
 NGK Spark Plug Co Ltd Japan
 O'Keefe Ceramics Inc CO
 Ortech Inc CA
 P-Ker Engineering NY
 Precision Ceramics FL
 PremaTech Advanced Ceramics MA
 Progressive Technology Inc CA
 Rauschert Industries Inc GA

Refrac Systems AZ
 Refractron Technologies Corp NY
 RocCera LLC NY
 Saint-Gobain Ceramics & Plastics MA
 Saint-Gobain Performance Ceramics & Refractories & Hexoloy SiC Materials MA
 Silicon Carbide Products Inc NY
 Starfire Systems Inc NY
 Suntech Advanced Ceramics (Shenzhen) Co Ltd China
 Superior Technical Ceramics Corp VT
 Technology Assessment and Transfer Inc (TA&T) MD
 Xiamen Unipretec Ceramic Technology Co Ltd China
 Zhengzhou Mission Ceramic Products Co Ltd China
 Zircoa Inc OH

Zirconia Products

Accuratus Corp NJ
 Actech Precision Ceramic (HK) Limited China
 AdTech Ceramics TN



AdValue Technology LLC AZ See ad on page 51
 Advanced Ceramic Technology CA
 Advanced Ceramics Manufacturing AZ
 Akron Porcelain & Plastics Co OH
 Associated Ceramics & Technology Inc PA
 Astral Material Industrial Co Ltd China
 Astro Met Advanced Ceramics Inc OH
 Beijing Cerametek Materials Co Ltd China
 Bharat Heavy Electricals Ltd India
 Ceramco Inc NH
 CeramTec North America Corp SC
 CeramTec-ETEC Germany
 CoorsTek CO
 EBL Products Inc CT
 ENrG Inc NY
 FCT Ingenieurkeramik GmbH Germany
 Ferro Ceramic Grinding Inc MA
 Ferrotec Ceramic Products China
 Imerys Fused Minerals Murg GmbH Germany
 Inducerceramic Canada
 Innovnano - Advanced Materials SA Portugal
 International Ceramic Engineering MA
 Israel Ceramic & Silicate Inst Israel
 Jyoti Ceramic Industries Pvt Ltd India
 Lithoz GmbH NY
 McDanel Advanced Ceramic Technologies LLC PA
 Morgan Advanced Materials CA
 MSE Supplies AZ
 Nanoe France
 NEVZ-Ceramics Close JSC Russia
 Nyacol Nano Technologies Inc MA
 O'Keefe Ceramics Inc CO
 Ortech Inc CA
 PicoParts Ltd Israel
 P-Ker Engineering NY
 Polymer Innovations Inc CA
 Precision Ferrites and Ceramics Inc CA
 PremaTech Advanced Ceramics MA
 Progressive Technology Inc CA



Rauschert Industries Inc GA
 Refractron Technologies Corp NY
 Robocasting Enterprises LLC NM
 RocCera LLC NY
 Saint-Gobain Ceramics & Plastics MA
 Saint-Gobain NorPro OH
 Suntech Advanced Ceramics (Shenzhen) Co Ltd China
 Superior Technical Ceramics Corp VT
 Wistra GmbH Germany
 Xiamen Unipretec Ceramic Technology Co Ltd China
 Zhengzhou Mission Ceramic Products Co Ltd China
 Zibo Guangtong Chemical Co Ltd China
 Zircoa Inc OH

ARTWARE

Ceramic Artware

Arlimin Industries CO
 Art On Ceramic NY
 Ceramic Arts Network OH
 Milestone Decal Art LLC NY
 StudioLX - Home Decor IL
 Tethon 3D NE
 Viridis3D LLC MA

Glass Artware

Arlimin Industries CO
 RISE Research Institutes of Sweden RISE Glass Sweden
 StudioLX - Home Decor IL
 Viridis3D LLC MA

Lighting

Akron Porcelain & Plastics Co OH
 Viridis3D LLC MA

Ornamental Artware

Ceramic Arts Network OH
 StudioLX - Home Decor IL
 Viridis3D LLC MA

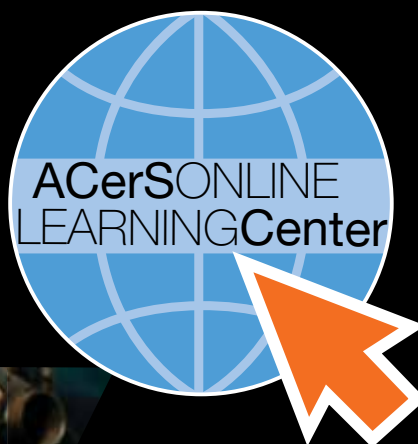
Pottery

ACCCO Inc/Burley Clay Products Co OH
 Arlimin Industries CO
 Ceramic Arts Network OH
 North Star Equipment Inc WA
 Peter Puggler Mfg Inc CA
 Petro Mold Company PA
 Ram Products Inc OH
 Sheffield Pottery MA
 StudioLX - Home Decor IL
 Viridis3D LLC MA

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 - ➔ Drying of Ceramics
 - ➔ Firing of Ceramics
 - ➔ Glaze Manufacturing for Industry

- ➔ Ceramic Manufacturing
- ➔ Glass Manufacturing
- ➔ Refractory Manufacturing
- ➔ Advanced Ceramics



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■ CERAMIC & METALLIC POWDERS & MATERIALS

Abrasive Grains

Alteo NA LLC OH
 Baikowski Malakoff Inc NC
 Electro Abrasives Corp NY
 FELDCO Intl CA
 GMA Industries Inc MI
 Imerys Refractory Minerals GA
 Kyanite Mining Corp VA
 Prince Minerals Inc (Prince International Corporation) TX
 Saint-Gobain Abrasives MA
 Saint-Gobain Ceramics & Plastics MA
 Specialty Glass Inc FL
 Washington Mills Electro Minerals Co NY

Adsorbants & Catalysts

GFS Chemicals Inc OH
 Saint-Gobain Ceramics & Plastics MA
 Saint-Gobain NorPro OH

Alumina, Activated

AluChem Inc OH
 Applied Ceramics Inc CA
 Denka Corp NY
 Momentive Performance Materials Inc NY
 Nanoe France



Paul O. Abbe Inc IL See ad on page 69
 Prince Minerals Inc (Prince International Corporation) TX
 Sauereisen Inc PA

Alumina, Calcined

Almatis Inc PA
 Alteo NA LLC OH
 AluChem Inc OH
 APF Recycling Inc OH
 Baikowski Malakoff Inc NC
 Denka Corp NY
 Electro Abrasives Corp NY
 Fusion Ceramics Inc OH
 Hindalco Industries Limited India
 Maryland Refractories Co OH
 Nabaltec AG Germany
 Nanoe France
 PIDC (Pacific Industrial Development Corporation) MI
 Prince Minerals Inc (Prince International Corporation) TX
 Refractory Minerals Co Inc PA
 Sauereisen Inc PA

Alumina, Fused

Alteo NA LLC OH
 APF Recycling Inc OH
 Denka Corp NY
 Electro Abrasives Corp NY
 GMA Industries Inc MI
 Imerys Refractory Minerals GA
 Lithoz GmbH NY
 McDanel Advanced Ceramic Technologies LLC PA
 Nanoe France
 Prince Minerals Inc (Prince International Corporation) TX
 Washington Mills Electro Minerals Co NY

Alumina, Fused Brown

Alteo NA LLC OH
 APF Recycling Inc OH
 BassTech Intl NJ
 Bosai Minerals Group Co Ltd China
 Electro Abrasives Corp NY
 GMA Industries Inc MI
 Imerys Refractory Minerals GA
 Washington Mills Electro Minerals Co NY

Alumina, Fused White

Alteo NA LLC OH
 APF Recycling Inc OH
 Electro Abrasives Corp NY
 Imerys Refractory Minerals GA
 Sauereisen Inc PA
 Washington Mills Electro Minerals Co NY

Alumina, High-Purity

Actech Precision Ceramic (HK) Limited China
 Alteo NA LLC OH
 AluChem Inc OH
 APF Recycling Inc OH
 Applied Ceramics Inc CA
 Associated Ceramics & Technology Inc PA
 Baikowski Malakoff Inc NC
 CARBO Texas
 CoorsTek CO
 Denka Corp NY
 International Ceramic Engineering MA
 Ipsen Ceramics IL
 Lithoz GmbH NY
 Materion Advanced Materials NY
 Materion Ceramics AZ
 Nanoe France
 PIDC (Pacific Industrial Development Corporation) MI
 Pred Materials International Inc NY
 Prince Minerals Inc (Prince International Corporation) TX
 Rauschert Industries Inc GA
 Sauereisen Inc PA
 Suntech Advanced Ceramics (Shenzhen) Co Ltd China
 Valley Design Corp MA
 Xiamen Unipretec Ceramic Technology Co Ltd China

Alumina, Hydrated

Almatis Inc PA
 Alteo NA LLC OH
 Denka Corp NY
 Fusion Ceramics Inc OH
 Hindalco Industries Limited India
 Nanoe France
 PIDC (Pacific Industrial Development Corporation) MI
 Prince Minerals Inc (Prince International Corporation) TX
 RE Carroll Inc PA

Alumina, Other Grades

Almatis Inc PA
 Alteo NA LLC OH
 Associated Ceramics & Technology Inc PA
 Baikowski Malakoff Inc NC
 CoorsTek CO
 Denka Corp NY
 Hindalco Industries Limited India
 Imerys Refractory Minerals GA
 Nanoe France
 PIDC (Pacific Industrial Development Corporation) MI
 Prince Minerals Inc (Prince International Corporation) TX
 Trinity Ceramic Supply Inc TX
 Wesbond Corp DE

Alumina, Reactive

Almatis Inc PA
 Alteo NA LLC OH
 AluChem Inc OH

Baikowski Malakoff Inc NC
 Denka Corp NY
 Hindalco Industries Limited India
 Nabaltec AG Germany
 Nanoe France
 Prince Minerals Inc (Prince International Corporation) TX

Alumina, Single Crystal

Denka Corp NY
 Nanoe France
 Prince Minerals Inc (Prince International Corporation) TX

Alumina, Tabular

Almatis Inc PA
 Alteo NA LLC OH
 AluChem Inc OH
 APF Recycling Inc OH
 Denka Corp NY
 GrainBound LLC PA
 Imerys Refractory Minerals GA
 Nanoe France
 Prince Minerals Inc (Prince International Corporation) TX
 Sauereisen Inc PA

Alumina, Zirconia Toughened

Actech Precision Ceramic (HK) Limited China
 Applied Ceramics Inc CA
 Associated Ceramics & Technology Inc PA
 CerCo LLC OH
 Denka Corp NY
 Innovnano - Advanced Materials SA Portugal
 Nanocerox UT
 Nanoe France
 PicoParts Ltd Israel
 PIDC (Pacific Industrial Development Corporation) MI
 Prince Minerals Inc (Prince International Corporation) TX
 Rauschert Industries Inc GA
 Sauereisen Inc PA
 Washington Mills Electro Minerals Co NY
 Xiamen Innovacera Advanced Materials Co Ltd China
 Zircoa Inc OH

Aluminum & Compounds

Atlantic Equipment Engineers NJ
 BassTech Intl NJ
 Denka Corp NY
 Hindalco Industries Limited India
 Leico Industries Inc NJ
 Refractory Minerals Co Inc PA
 Valley Design Corp MA
 Xiamen Unipretec Ceramic Technology Co Ltd China

Aluminum Nitride

Actech Precision Ceramic (HK) Limited China
 Applied Ceramics Inc CA
 Atlantic Equipment Engineers NJ
 Bullen OH
 Centerline Technologies MA
 Denka Corp NY
 Goodfellow Corp PA
 International Ceramic Engineering MA
 North American Hoganas PA
 Pred Materials International Inc NY
 Reade Advanced Materials RI
 Surmet Corp MA
 Toyal America Inc IL
 Valley Design Corp MA

Aluminum Silicate

Goodfellow Corp PA
 Sauereisen Inc PA

Antimony & Compounds

Alfa Aesar Johnson Matthey MA
Atlantic Equipment Engineers NJ
Goodfellow Corp PA
Pred Materials International Inc NY

Arsenic Oxide

Alfa Aesar Johnson Matthey MA

Barium & Compounds

Alfa Aesar Johnson Matthey MA
American Elements Inc CA Outside back cover, 54
BassTech Intl NJ
Bosai Minerals Group Co Ltd China
CerPoTech AS Norway
FELDCO Intl CA
GFS Chemicals Inc OH
Trinity Ceramic Supply Inc TX

Barium Carbonate

BassTech Intl NJ
Fusion Ceramics Inc OH
Hexion Inc OH

Barium Titanate

AVX Corp SC
BassTech Intl NJ
Beijing Cerametek Materials Co Ltd China
CerPoTech AS Norway
Euro Support Advanced Materials The Netherlands
Haiku Tech Inc FL
Hexion Inc OH
nGimat LLC KY

Bauxite, Sintered

Alteo NA LLC OH

Beryllium & Compounds

APF Recycling Inc OH
Centerline Technologies MA
Leico Industries Inc NJ
Materion Advanced Materials NY
Materion Ceramics AZ

Bismuth & Compounds

Atlantic Equipment Engineers NJ
Beijing Cerametek Materials Co Ltd China
CerPoTech AS Norway
FELDCO Intl CA
Fusion Ceramics Inc OH
nGimat LLC KY

Boric Acid

Paul O. Abbe Inc IL
Sauereisen Inc PA

See ad on page 69

U.S. Borax Inc I Rio Tinto IL

See ad on page 73

Boron & Compounds

Atlantic Equipment Engineers NJ
Beijing Cerametek Materials Co Ltd China
Denka Corp NY
Electro Abrasives Corp NY
FELDCO Intl CA
Fusion Ceramics Inc OH

New Tech Ceramics Inc IA
North American Hoganas PA



U.S. Borax Inc I Rio Tinto IL

See ad on page 73

Boron Carbide

Atlantic Equipment Engineers NJ
CoorsTek CO
Custom Processing Services PA
Denka Corp NY
Dunhua Zhengxing Abrasive Co Ltd China
Electro Abrasives Corp NY
FELDCO Intl CA
Free Form Fibers NY
Goodfellow Corp PA
North American Hoganas PA
Reade Advanced Materials RI
Superior Graphite Co IL
Washington Mills Electro Minerals Co NY

Boron Nitride

Atlantic Equipment Engineers NJ
Denka Corp NY
Diamorph AB UK
FELDCO Intl CA
Goodfellow Corp PA
International Ceramic Engineering MA
Momentive Performance Materials Inc NY
North American Hoganas PA
Precision Ceramics FL
Reade Advanced Materials RI
Saint-Gobain Ceramics & Plastics MA
Xiamen Unipretec Ceramic Technology Co Ltd China

Cadmium & Compounds

Alfa Aesar Johnson Matthey MA
FELDCO Intl CA
GFS Chemicals Inc OH
Hunter Chemical LLC PA

Calcium & Compounds

C&L Development Corp CA
CerPoTech AS Norway
Denka Corp NY
GFS Chemicals Inc OH
Prince Minerals Inc (Prince International Corporation) TX

Calcium Aluminates

Almatris Inc PA
CerPoTech AS Norway
Gorka Cement Poland See ad on page 71
Mineral Research Processing France
nGimat LLC KY
Sauereisen Inc PA

Calcium Carbonate

Arkema Inc PA
Fusion Ceramics Inc OH
Prince Minerals Inc (Prince International Corporation) TX
RE Carroll Inc PA
Unimin Corp CT

Calcium Silicate

Fusion Ceramics Inc OH
Mineral Research Processing France
Sauereisen Inc PA

Carbon Fibers

Goodfellow Corp PA

Carbons, Carbon Black

Cancarb Limited Canada

Carbons, Diamond

Goodfellow Corp PA

Carbons, Graphite

APF Recycling Inc OH
FELDCO Intl CA
Goodfellow Corp PA
Pred Materials International Inc NY
Semco Carbon OH
Superior Graphite Co IL

Cements

Aremco Products Inc NY
ESL ElectroScience PA
Gwent Electronic Materials Ltd UK

Cements, Refractory

Almatris Inc PA
Aremco Products Inc NY
Diamorph AB UK
Gorka Cement Poland See ad on page 71
Kerneos Inc VA
Mineral Research Processing France
Sauereisen Inc PA
Unifrax I LLC NY

Cerium & Compounds

American Elements Inc CA Outside back cover, 54
Arlimin Industries CO
CerPoTech AS Norway
FELDCO Intl CA
GFS Chemicals Inc OH
nGimat LLC KY
PIDC (Pacific Industrial Development Corporation) MI
Trans-Tech Inc a subsidiary of Skyworks Solutions Inc MD See ad on page 81
Treibacher Industrie AG Austria

Cerments

Gorka Cement Poland

See ad on page 71

Chamotte

Imerys Refractory Minerals GA

Chrome & Compounds

Arlimin Industries CO
Atlantic Equipment Engineers NJ
CerPoTech AS Norway
Hunter Chemical LLC PA
Monofrax LLC NY
North American Hoganas PA

Clay Bodies, Formulated

American Art Clay Co Inc IN
Imerys GA
Laguna Clay Co CA
Sheffield Pottery MA
Tethon 3D NE
Unimin Corp CT

Cobalt & Compounds

Arlimin Industries CO
 Atlantic Equipment Engineers NJ
 Beijing Cerametek Materials Co Ltd China
 Ceramic Color & Chemical Mfg Co PA
 CerPoTech AS Norway
 FELDCO Intl CA
 Fusion Ceramics Inc OH
 Goodfellow Corp PA
 Hunter Chemical LLC PA
 nGimat LLC KY

Copper & Compounds

American Chemet Corp IL
 APF Recycling Inc OH
 Atlantic Equipment Engineers NJ
 Beijing Cerametek Materials Co Ltd China
 Ceramic Color & Chemical Mfg Co PA
 CerPoTech AS Norway
 Goodfellow Corp PA
 Shoei Chemical Inc Japan

Dielectric Powders

AVX Corp SC
 CerPoTech AS Norway
 Euro Support Advanced Materials The Netherlands
 Gwent Electronic Materials Ltd UK
 Haiku Tech Inc FL
 North American Hoganas PA
Trans-Tech Inc a subsidiary of
Skyworks Solutions Inc MD See ad on page 81

Dysprosium Oxide

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 C&L Development Corp CA
 CerPoTech AS Norway
 Leico Industries Inc NJ
 PIDC (Pacific Industrial Development Corporation) MI
 Treibacher Industrie AG Austria

Electrically Conducting Powders

BassTech Intl NJ
 CerPoTech AS Norway
 Hunter Chemical LLC PA
 Innovnano - Advanced Materials SA Portugal

Erbium Oxide

C&L Development Corp CA
 CerPoTech AS Norway
 FELDCO Intl CA
 Leico Industries Inc NJ
 MSE Supplies AZ
 PIDC (Pacific Industrial Development Corporation) MI
 Treibacher Industrie AG Austria

Europium Oxide

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 C&L Development Corp CA
 CerPoTech AS Norway
 Leico Industries Inc NJ
 MSE Supplies AZ
 PIDC (Pacific Industrial Development Corporation) MI
 Treibacher Industrie AG Austria

Ferrites & Ferromagnetics

Centerline Technologies MA
 Powder Processing & Technology LLC IN
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Fibers, Ceramic

Free Form Fibers NY
 MemPro Materials Corp
 Thermal Products Co Inc GA
 Unifrax I LLC NY
 Wesbond Corp DE

Fibers, Glass

BassTech Intl NJ
Mo-Sci Corp MO See ad on page 95
 RISE Research Institutes of Sweden RISE Glass Sweden
 Schott North America Inc NY
 Unifrax I LLC NY

Fluorides

BassTech Intl NJ
 Beijing Cerametek Materials Co Ltd China
 Sauereisen Inc PA

Frit

Ceradyne Inc a 3M Co KY
 Ceramic Color & Chemical Mfg Co PA
 Fusion Ceramics Inc OH
 Laguna Clay Co CA
 RISE Research Institutes of Sweden RISE Glass Sweden
 Trinity Ceramic Supply Inc TX
 Zibo Guangtong Chemical Co Ltd China

Gadolinium Oxide

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 CerPoTech AS Norway
 PIDC (Pacific Industrial Development Corporation) MI

Gallium & Compounds

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American Elements Inc CA Outside back cover, 54
 Beijing Cerametek Materials Co Ltd China
 CerPoTech AS Norway
 Goodfellow Corp PA
 MSE Supplies AZ

Germanium & Compounds

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American Elements Inc CA Outside back cover, 54
 Beijing Cerametek Materials Co Ltd China
 C&L Development Corp CA
 MSE Supplies AZ
 Treibacher Industrie AG Austria

Grain, Refractory

Christy Minerals LLC MO
 Imerys Refractory Minerals GA

Graphite

APF Recycling Inc OH
 Applied Ceramics Inc CA
 Aremco Products Inc NY
 Beijing Cerametek Materials Co Ltd China
 CoorsTek CO
 Momentive Performance Materials Inc NY
 Semco Carbon OH
 Superior Graphite Co IL
TevTech LLC MA See ad on page 89

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 Pred Materials International Inc NY

Iron & Compounds

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 CerPoTech AS Norway
 GFS Chemicals Inc OH
 Goodfellow Corp PA
 Kyantite Mining Corp VA
 Leico Industries Inc NJ
 Prince Minerals Inc (Prince International Corporation) TX

Iron Oxide

Fusion Ceramics Inc OH
 Prince Minerals Inc (Prince International Corporation) TX
 Reade Advanced Materials RI

Lanthanides (also see Rare-Earths)

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 C&L Development Corp CA
 FELDCO Intl CA
 GFS Chemicals Inc OH
 MSE Supplies AZ
 Nanocerox UT
 PIDC (Pacific Industrial Development Corporation) MI
 Treibacher Industrie AG Austria

Lanthanum & Compounds

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 GFS Chemicals Inc OH
 Goodfellow Corp PA
 North American Hoganas PA
 PIDC (Pacific Industrial Development Corporation) MI

Lead & Compounds

Goodfellow Corp PA

Lithium & Compounds

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 Beijing Cerametek Materials Co Ltd China
 Ceramic Color & Chemical Mfg Co PA
 CerPoTech AS Norway
 GFS Chemicals Inc OH
 MSE Supplies AZ
 nGimat LLC KY
 Pred Materials International Inc NY
 Trinity Ceramic Supply Inc TX

Magnesia, Fused

APF Recycling Inc OH
 Du-Co Ceramics Company PA
 Fluid Energy Processing & Equipment Co PA
 Washington Mills Electro Minerals Co NY

Magnesia-Alumina, Sintered

Baikowski Malakoff Inc NC
 Fluid Energy Processing & Equipment Co PA

Magnesium & Compounds

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 BassTech Intl NJ
 Bosai Minerals Group Co Ltd China
 CerPoTech AS Norway

FELDCO Intl CA
 Fusion Ceramics Inc OH
 GFS Chemicals Inc OH
 Goodfellow Corp PA
 Pred Materials International Inc NY
 Prince Minerals Inc (Prince International Corporation) TX
 Atlantic Equipment Engineers NJ
 BassTech Intl NJ
 CerPoTech AS Norway
 Fusion Ceramics Inc OH
 Goodfellow Corp PA
 nGimat LLC KY
 Prince Minerals Inc (Prince International Corporation) TX
 RE Carroll Inc PA

Metallic Salts

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 Hunter Chemical LLC PA

Metallizing Compounds

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 Elcon Precision LLC CA
 Gwent Electronic Materials Ltd UK
 Sigma Advanced Materials NY

Microspheres, Hollow

Washington Mills Electro Minerals Co NY

Molybdenum & Compounds

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 CerPoTech AS Norway
 Elcon Precision LLC CA
 GFS Chemicals Inc OH

Nanomaterials



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 Cerion Nanomaterials NY
 CerPoTech AS Norway
 Innovnano - Advanced Materials SA Portugal
 MSE Supplies AZ
 Nanocerox UT
 nGimat LLC KY
 Nyacol Nano Technologies Inc MA
 Pred Materials International Inc NY
TevTech LLC MA See ad on page 89

Neodymium Oxide

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 C&L Development Corp CA
 CerPoTech AS Norway
 Leico Industries Inc NJ
 MSE Supplies AZ
 PIDC (Pacific Industrial Development Corporation) MI

Nickel & Compounds

American Chemet Corp IL
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 APF Recycling Inc OH
 Arlimin Industries CO
 Atlantic Equipment Engineers NJ
 Ceramic Color & Chemical Mfg Co PA
 CerPoTech AS Norway
 FELDCO Intl CA
 GFS Chemicals Inc OH
 Hunter Chemical LLC PA
 Shoei Chemical Inc Japan

Niobium & Compounds

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 CerPoTech AS Norway
 FELDCO Intl CA
 Leico Industries Inc NJ

Organic Precursors

Starfire Systems Inc NY

Pastes, Conductor

Aremco Products Inc NY
 Haiku Tech Inc FL
 Polymer Innovations Inc CA
 Sauereisen Inc PA
 Shoei Chemical Inc Japan

Phosphates

Arkema Inc PA
 BassTech Intl NJ
 nGimat LLC KY
 Refractory Minerals Co Inc PA
 Sauereisen Inc PA

Piezoelectric Compositions

APC International Ltd PA
 AVX Corp SC
 CerPoTech AS Norway
 Polymer Innovations Inc CA
 Sparkler Ceramics Pvt Ltd India

Pigments

Arlimin Industries CO
 Ceramic Color & Chemical Mfg Co PA
 Fusion Ceramics Inc OH
 Hunter Chemical LLC PA
 Mason Color Works Inc OH
 Sauereisen Inc PA
 Wistra GmbH Germany

Plaster, Gypsum

Sheffield Pottery MA

Plaster, Industrial

Sheffield Pottery MA

Potassium & Compounds

CerPoTech AS Norway
 GFS Chemicals Inc OH

Powdered Metals

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 Arlimin Industries CO
 Beijing Cerametek Materials Co Ltd China
 Cancarb Limited Canada
 Hunter Chemical LLC PA
 Pred Materials International Inc NY

Praseodymium Oxide

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 C&L Development Corp CA

CerPoTech AS Norway
 Leico Industries Inc NJ
 Nanocerox UT
 PIDC (Pacific Industrial Development Corporation) MI

Precious Metals

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 APF Recycling Inc OH
 Gwent Electronic Materials Ltd UK
 Leico Industries Inc NJ
 Polymer Innovations Inc CA
 Shoei Chemical Inc Japan

Rare-Earth Titanates

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See ad on page 81

Rare-Earths

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 C&L Development Corp CA
 FELDCO Intl CA
 GFS Chemicals Inc OH
 Innovnano - Advanced Materials SA Portugal
 MSE Supplies AZ
 Nanocerox UT
 PIDC (Pacific Industrial Development Corporation) MI
 Pred Materials International Inc NY
 Spontaneous Materials CO
 Treibacher Industrie AG Austria
 Wistra GmbH Germany

Refractory Oxides

Arlimin Industries CO
 Christy Minerals LLC MO
 Hunter Chemical LLC PA
 Innovnano - Advanced Materials SA Portugal
 Leico Industries Inc NJ
 nGimat LLC KY

Resins, Molding

Hexion Inc OH
 Polymer Innovations Inc CA
 Starfire Systems Inc NY

Samarium Oxide

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 C&L Development Corp CA
 CerPoTech AS Norway
 Nanocerox UT
 PIDC (Pacific Industrial Development Corporation) MI

Sand, Foundry

Kyanite Mining Corp VA
 U.S. Silica Co MD

Sand, Glass

Fusion Ceramics Inc OH
 RISE Research Institutes of Sweden RISE Glass Sweden
 U.S. Silica Co MD

Sand, High-Purity Silica

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 Maryland Refractories Co OH
 U.S. Silica Co MD
 Unimin Corp CT

Scandium & Compounds

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 FELDCO Intl CA
 Leico Industries Inc NJ
 Nanocerox UT
 Trinity Ceramic Supply Inc TX

Selenium & Compounds

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 FELDCO Intl CA
 Pred Materials International Inc NY

Semiconducting Powders



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SiAlON Powder

Pred Materials International Inc NY

Silica

Arkema Inc PA
 Denka Corp NY
 Ipsen Ceramics IL
 Maryland Refractories Co OH
 Momentive Performance Materials Inc NY
 Nanocerox UT
 Saint-Gobain Ceramics & Plastics MA
 Sauereisen Inc PA
 Sibelco Benelux Belgium
 U.S. Silica Co MD

Silica, Fused

APF Recycling Inc OH
 BassTech Intl NJ
 Bosai Minerals Group Co Ltd China
 Centerline Technologies MA
 Industrial Ceramic Products Inc OH
 Ipsen Ceramics IL
 Momentive Performance Materials Inc NY
 Technical Glass Products Inc Ohio
 Valley Design Corp MA

Silicates

BassTech Intl NJ
 Denka Corp NY
 Nanocerox UT
 Sauereisen Inc PA

Silicon & Compounds

Atlantic Equipment Engineers NJ
 Elkem Metals Inc PA
 FELDCO Intl CA
 McDanel Advanced Ceramic Technologies LLC PA
 Reade Advanced Materials RI
 Valley Design Corp MA

Silicon Carbide

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 Ortech Inc CA
 Pred Materials International Inc NY
 Rauschert Industries Inc GA
 Saint-Gobain Ceramics & Plastics MA
 Starfire Systems Inc NY
 Suntech Advanced Ceramics (Shenzhen) Co Ltd China
 Superior Graphite Co IL
 Texers Technical Ceramics Inc Canada
 Treibacher Industrie AG Austria
 Valley Design Corp MA
 Washington Mills Electro Minerals Co NY

Silicon Nitride

Alteo NA LLC OH
 Applied Ceramics Inc CA
 Atlantic Equipment Engineers NJ
 Bullen OH
 CerCo LLC OH
 CoorsTek CO
 Denka Corp NY
 FELDCO Intl CA
 Goodfellow Corp PA
 International Ceramic Engineering MA
 McDanel Advanced Ceramic Technologies LLC PA
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 Suntech Advanced Ceramics (Shenzhen) Co Ltd China
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 Xiamen Unipretec Ceramic Technology Co Ltd China

Sodium & Compounds

Atlantic Equipment Engineers NJ
 GFS Chemicals Inc OH

Spheres, Ceramic

Saint-Gobain NorPro OH

Spheres, Glass

Imerys Refractory Minerals GA
Mo-Sci Corp MO **See ad on page 95**
 RISE Research Institutes of Sweden RISE Glass Sweden

Strontium & Compounds

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 CerPoTech AS Norway
 Fusion Ceramics Inc OH
 GFS Chemicals Inc OH
 nGimat LLC KY

Superabrasives

Alteo NA LLC OH
 Diamond Industrial Tools Inc IL
 Dianamic Abrasive Products Inc MI
 Saint-Gobain Ceramics & Plastics MA

Superconducting Powders

Alfa Aesar Johnson Matthey MA
 nGimat LLC KY

Tantalum Metal Powder

Leico Industries Inc NJ

Tantalum Oxide

CerPoTech AS Norway
 FELDCO Intl CA
 PIDC (Pacific Industrial Development Corporation) MI

Terbium Oxide

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 CerPoTech AS Norway
 Leico Industries Inc NJ
 Nanocerox UT

Thickening Agents

Lubrizol Performance Coating OH

Thick-Film Materials

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 ESL ElectroScience PA
 New Tech Ceramics Inc IA
 Polymer Innovations Inc CA
 Shoei Chemical Inc Japan

Thin-Film Materials



American Elements Inc CA **Outside back cover, 54**

Cerakote Ceramic Coatings OR
 CerPoTech AS Norway
 FELDCO Intl CA
 Innovnano - Advanced Materials SA Portugal
 Materion Advanced Materials NY
 New Tech Ceramics Inc IA
 Valley Design Corp MA

Tin & Compounds

Arlimin Industries CO
 CerPoTech AS Norway
 FELDCO Intl CA
 Goodfellow Corp PA
 Trinity Ceramic Supply Inc TX

Titanium & Compounds

APF Recycling Inc OH
 Atlantic Equipment Engineers NJ
 C&L Development Corp CA
 FELDCO Intl CA
 Goodfellow Corp PA
 Leico Industries Inc NJ
 Nanocerox UT
 North American Hoganas PA
 TAM Ceramics NY

Titanium Carbide

Atlantic Equipment Engineers NJ
 Beijing Cerametek Materials Co Ltd China
 FELDCO Intl CA
 North American Hoganas PA
 Reade Advanced Materials RI

Titanium Diboride

Dunhua Zhengxing Abrasive Co Ltd China
 FELDCO Intl CA
 Momentive Performance Materials Inc NY
 New Tech Ceramics Inc IA
 North American Hoganas PA
 Pred Materials International Inc NY
 Surmet Corp MA

Titanium Dioxide

BassTech Intl NJ
 Beijing Cerametek Materials Co Ltd China
 FELDCO Intl CA

Fusion Ceramics Inc OH
 Nanocerox UT
 nGimat LLC KY
 Pred Materials International Inc NY

Titanium Nitride

Atlantic Equipment Engineers NJ
 FELDCO Intl CA
 North American Hoganas PA
 Pred Materials International Inc NY

Tubes

Technical Glass Products Inc Ohio

Tungsten Carbide

Associated Ceramics & Technology Inc PA
 Atlantic Equipment Engineers NJ
 C&L Development Corp CA
 Centerline Technologies MA
 Custom Processing Services PA
 FELDCO Intl CA
 MSE Supplies AZ
 North American Hoganas PA
 PicoParts Ltd Israel
 Pred Materials International Inc NY

Tungsten Oxide

CerPoTech AS Norway
 FELDCO Intl CA

Uranium & Compounds

Wistra GmbH Germany

Vanadium & Compounds

Atlantic Equipment Engineers NJ
 CerPoTech AS Norway
 FELDCO Intl CA

Wetting Agents

Lubrizol Performance Coating OH

Yttria

APF Recycling Inc OH
 Associated Ceramics & Technology Inc PA
 Bullen OH
 CoorsTek CO
 ESL ElectroScience PA
 Innovnano - Advanced Materials SA Portugal
 Nanocerox UT
 nGimat LLC KY
 North American Hoganas PA
 PIDC (Pacific Industrial Development Corporation) MI
 Pred Materials International Inc NY
 Washington Mills Electro Minerals Co NY

Yttrium & Compounds

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American Elements Inc CA **Outside back cover, 54**
 C&L Development Corp CA
 CerPoTech AS Norway
 GFS Chemicals Inc OH
 Nanocerox UT
 nGimat LLC KY
 PIDC (Pacific Industrial Development Corporation) MI

Zinc & Compounds

CerPoTech AS Norway
 FELDCO Intl CA
 Leico Industries Inc NJ
 Prince Minerals Inc (Prince International Corporation) TX
 RE Carroll Inc PA
 Sauereisen Inc PA
TevTech LLC MA **See ad on page 89**

Zinc Borate

U.S. Borax Inc | Rio Tinto IL **See ad on page 73**

Zinc Oxide

American Chemet Corp IL
 FELDCO Intl CA
 Fusion Ceramics Inc OH
 nGimat LLC KY
 Prince Minerals Inc (Prince International Corporation) TX
 Sauereisen Inc PA
 uttam industries India

Zirconia

Applied Ceramics Inc CA
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 Custom Processing Services PA
 Innovnano - Advanced Materials SA Portugal
 International Ceramic Engineering MA
 Leico Industries Inc NJ
 Nanocerox UT
 Nanoe France
 nGimat LLC KY
 Ortech Inc CA
 PIDC (Pacific Industrial Development Corporation) MI
 PremaTech Advanced Ceramics MA
 Rauschert Industries Inc GA
 Saint-Gobain Ceramics & Plastics MA
 Sauereisen Inc PA
 Suntech Advanced Ceramics (Shenzhen) Co Ltd China
 TAM Ceramics NY
 Washington Mills Electro Minerals Co NY
 Xiamen Unipretec Ceramic Technology Co Ltd China
 Zibo Guangtong Chemical Co Ltd China
 Zircoa Inc OH

Zirconia, Engineering-Grade

Innovnano - Advanced Materials SA Portugal
 Leico Industries Inc NJ
 McDanel Advanced Ceramic Technologies LLC PA
 Nanoe France
 Zibo Guangtong Chemical Co Ltd China
 Zircoa Inc OH

Zirconia, High-Purity

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 CARBO Texas
 CoorsTek CO
 Innovnano - Advanced Materials SA Portugal
 International Ceramic Engineering MA
 Nanocerox UT
 Nanoe France
 Sauereisen Inc PA
 Zibo Guangtong Chemical Co Ltd China

Zirconia, Refractory-Grade

McDanel Advanced Ceramic Technologies LLC PA
 Nanoe France
 Washington Mills Electro Minerals Co NY
 Zircoa Inc OH

Zirconium & Compounds

Atlantic Equipment Engineers NJ
 C&L Development Corp CA
 CerPoTech AS Norway
 FELDCO Intl CA
 Goodfellow Corp PA
 Innovnano - Advanced Materials SA Portugal
 Luxfer MEL Technologies NJ
 Monofrax LLC NY
 PIDC (Pacific Industrial Development Corporation) MI
 Saint-Gobain Ceramics & Plastics MA
 Zibo Guangtong Chemical Co Ltd China

Zirconium Carbide

Cancarb Limited Canada
 North American Hoganas PA

Zirconium Carbonate

C&L Development Corp CA
 Zibo Guangtong Chemical Co Ltd China

Zirconium Diboride

North American Hoganas PA
 North American Hoganas PA

CLAY & NATURAL MINERALS**Bauxite**

APF Recycling Inc OH
 Bosai Minerals Group Co Ltd China
 Fluid Energy Processing & Equipment Co PA
 Hindalco Industries Limited India
 Imerys Refractory Minerals GA
 Prince Minerals Inc (Prince International Corporation) TX

Bentonite

Custom Processing Services PA
 Reade Advanced Materials RI
 Trinity Ceramic Supply Inc TX
 Vanderbilt Minerals LLCCT

Borax

borax.com/dehybor

U.S. Borax Inc | Rio Tinto IL

See ad on page 73

Chromite

Prince Minerals Inc (Prince International Corporation) TX

Clays, Ball

Fusion Ceramics Inc OH
 Imerys GA
 Old Hickory Clay Co KY
 Sheffield Pottery MA
 Sibelco Benelux Belgium
 Trinity Ceramic Supply Inc TX
 Unimin Corp CT

Clays, China

Fusion Ceramics Inc OH
 Imerys GA
 Old Hickory Clay Co KY
 Sheffield Pottery MA
 Sibelco Benelux Belgium
 Vanderbilt Minerals LLC CT

Clays, Enamel

Old Hickory Clay Co KY
 RISE Research Institutes of Sweden RISE Glass Sweden
 Sibelco Benelux Belgium
 Vanderbilt Minerals LLC CT

Clays, Engobe

Imerys GA
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Aley Refractories Co MO
 Christy Minerals LLC MO

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Maryland Refractories Co OH
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Peter Pugger Mfg Inc CA
Riverside Refractories Inc--Allied Mineral Products AL
Sheffield Pottery MA
Sibelco Benelux Belgium

Clays, Glaze

Imerys GA
Old Hickory Clay Co KY
Peter Pugger Mfg Inc CA
Sheffield Pottery MA
Sibelco Benelux Belgium
Vanderbilt Minerals LLC CT

Clays, Stoneware

Christy Minerals LLC MO
Old Hickory Clay Co KY
Peter Pugger Mfg Inc CA
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Reade Advanced Materials RI
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Diatomaceous Earth

Reade Advanced Materials RI

Dolomite

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Trinity Ceramic Supply Inc TX

Feldspar

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Fusion Ceramics Inc OH
Imerys GA
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Sheffield Pottery MA
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Flint

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Kaolin

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CARBO Texas
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Fusion Ceramics Inc OH
Imerys GA
Imerys Refractory Minerals GA
M&M Clays Inc GA
Old Hickory Clay Co KY
RE Carroll Inc PA
Reade Advanced Materials RI
Sheffield Pottery MA
Trinity Ceramic Supply Inc TX
U.S. Silica Co MD
Vanderbilt Minerals LLC CT

Kyanite

Kyanite Mining Corp VA

Lime & Limestone

Prince Minerals Inc (Prince International Corporation) TX
RE Carroll Inc PA

Lithium Minerals

Avalon Advanced Materials Inc Canada
Fusion Ceramics Inc OH

Magnesite

APF Recycling Inc OH
Bosai Minerals Group Co Ltd China
Fluid Energy Processing & Equipment Co PA
Imerys Refractory Minerals GA

Mica

Imerys GA

Montmorillonite

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Mullite

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Imerys Refractory Minerals GA
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Kyanite Mining Corp VA
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Reade Advanced Materials RI
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Washington Mills Electro Minerals Co NY

Nepheline Syenite

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Sheffield Pottery MA
Sibelco Benelux Belgium
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Olivine

Prince Minerals Inc (Prince International Corporation) TX
Sibelco Benelux Belgium

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Quartz

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Imerys Refractory Minerals GA
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Spinel

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Baikowski Malakoff Inc NC
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Steatite

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Cancarb Limited Canada
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Foundation Floors FL
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Analytical Services

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Alfred University NY

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CoorsTek CO
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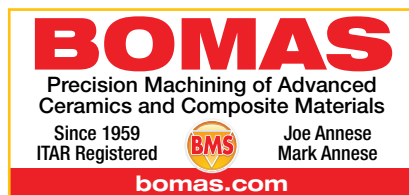


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Air Force Civil Engineer Center FL
CoorsTek CO

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See ad on page 101

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Ceritherm France
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Hitech Materials Pty Ltd NSW

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Lithoz GmbH NY
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 AVEKA MN



Bekeson Glass LLC MS

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CerPoTech AS Norway

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 CeramTec North America Corp SC
 CerCo LLC OH
 CoorsTek CO
 Du-Co Ceramics Company PA
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 Lithoz GmbH NY
 Morgan Technical Ceramics Auburn CA
 Ortech Inc CA
 P-Ker Engineering NY
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 Silicon Carbide Products Inc NY
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 Technology Assessment and Transfer Inc (TA&T) MD
 Tethon 3D NE

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 Fosbel Inc OH
 Refractory Consulting Services OH
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Screen Printing

Aremco Products Inc NY
 Gwent Electronic Materials Ltd UK
 Haiku Tech Europe BV The Netherlands
 Haiku Tech Inc FL

Screening, Custom

AVEKA MN

Bekeson Glass LLC MS

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CerPoTech AS Norway
 Fluid Energy Processing & Equipment Co PA
 General Spray Drying Service Inc NJ
 Reade Advanced Materials RI

Seals

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 Bharat Heavy Electricals Ltd India
 CerCo LLC OH
 Dunhua Zhengxing Abrasive Co Ltd China
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 Ortech Inc CA
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Powder Processing & Technology LLC IN



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Toll Firing, Contract

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Astro Met Advanced Ceramics Inc OH
CeramTec North America Corp SC
Christy Minerals LLC MO
FCT Ingenieurkeramik GmbH Germany
FCT Systeme GmbH Germany



Harrop Industries Inc OH See ad on page 58

Ipsen Ceramics IL

Oxy-Gon Industries Inc NH See ad on page 85

Refrac Systems AZ
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Engobes

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Ceramic Color & Chemical Mfg Co PA
Fusion Ceramics Inc OH
Mason Color Works Inc OH

Frits

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Ceramic Color & Chemical Mfg Co PA
Fusion Ceramics Inc OH
RISE Research Institutes of Sweden RISE Glass Sweden
Trinity Ceramic Supply Inc TX

Glazes

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Fusion Ceramics Inc OH
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Master Bond Inc NJ

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Burners

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HED INTl Inc NJ
Swindell Dressler Intl Co PA
Zenith China

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Euro Support Advanced Materials The Netherlands
Fluid Energy Processing & Equipment Co PA

Harper International NY

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Nabertherm Inc DE
Raymond Bartlett Snow-Schneck Processing IL
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Thermcraft Inc NC
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Zenith China

Cars, Dryer

Zenith China

Cars, Kiln

Basic Machinery Co Inc NC
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Deltech Inc (Deltech Furnaces) CO

Inside front cover

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Magneco Metrel Inc IL
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Wistra GmbH Germany
Zenith China

Cars, Transfer

Swindell Dressler Intl Co PA
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Controllers, Combustion

Air Products PA
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Controllers, Furnace

Carbolite Gero UK
Nabertherm Inc DE
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Controllers, Temperature

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Edward Orton Jr Ceramic Foundation OH
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Optocon AG Germany
Paragon Industries LP TX
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Haiku Tech Inc FL

I Squared R Element Co NY

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Applied Test Systems Inc PA
Control Instruments Corp NJ

Furnaces

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Cober Muegge LLC CT



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Furnace Products & Services Inc PA

Gasbarre Products Inc PA

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Goceram AB Sweden

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Harrop Industries Inc OH

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Swindell Dressler Intl Co PA
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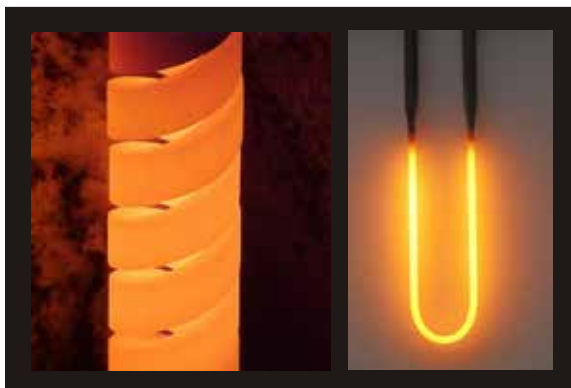
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 Wyssmont Co NJ

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 Wyssmont Co NJ

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 Ceradyne Inc a 3M Co KY
 CM Furnaces Inc NJ



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 RISE Research Institutes of Sweden RISE Glass Sweden
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Oxy-Gon Industries Inc NH See ad on page 85
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Furnaces, Laboratory

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 Goceram AB Sweden
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Heating Elements

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Furnace Products & Services Inc PA



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Kilns, Bell

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Kilns, Conveyor

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Kilns, Elevator

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Kilns, Envelope

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Kilns, Pusher Plate

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 Lucifer Furnaces Inc PA
 Recco Furnaces CA

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Kilns, Roller Hearth

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 Ceritherm France
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Harrop Industries Inc OH
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 Nutec Bickley Mexico
 Swindell Dressler Intl Co PA
 Takasago Industry Co Ltd Japan
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Kilns, Rotary

Ceritherm France
 CM Furnaces Inc NJ



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Kilns, Test/Lab

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Kilns, Tunnel (Continuous)

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Deltech Inc (Deltech Furnaces) CO Inside front cover
 Euro Support Advanced Materials The Netherlands
Harper International NY See ad on page 77



Harrop Industries Inc OH See ad on page 58
 Keith Co CA
 Nutec Bickley Mexico
 Recco Furnaces CA
 Swindell Dressler Intl Co PA
 Takasago Industry Co Ltd Japan
 Wistra GmbH Germany

Lehrs

Ceramic Services Inc PA
Harrop Industries Inc OH See ad on page 58
 Keith Co CA
 Recco Furnaces CA

Microwave Systems

Bharat Heavy Electricals Ltd India
 Ceralink Inc NY
 Ceritherm France
 CM Furnaces Inc NJ
 Cober Muegge LLC CT
 Gerling Applied Engineering Inc CA
 Harper International NY

See ad on page 77



Harrop Industries Inc OH
 RocCera LLC NY
 Takasago Industry Co Ltd Japan

See ad on page 58

Oxygen Supply

Air Products PA

Process/Quality Control Systems

Applied Test Systems Inc PA
 Datapaq Inc NH
 General Glass Equipment Co NJ
 Materials Research Furnaces Inc NH

Pyrometric Cones/Plaques

American Art Clay Co Inc IN
 Edward Orton Jr Ceramic Foundation OH
 Industrial Ceramic Products Inc OH
 PSH Kilns & Furnaces Canada
 Trinity Ceramic Supply Inc TX

Sensors, Temperature

Datapaq Inc NH
 Penn Tool Co NJ
 Zibo Guangtong Chemical Co Ltd China

Thermocouples & Accessories

AdValue Technology LLC AZ See ad on page 51
 American Art Clay Co Inc IN
 American Isostatic Presses OH
 CM Furnaces Inc NJ
 Datapaq Inc NH
Gasbarre Products Inc PA See ad on page 93
Harrop Industries Inc OH See ad on page 58
 Keith Co CA
 Leico Industries Inc NJ
 Materials Research Furnaces Inc NH
 McDanel Advanced Ceramic Technologies LLC PA
 PSH Kilns & Furnaces Canada
 Quintus Technologies LLC OH
 Recco Furnaces CA
Verder Scientific Inc PA See ad on page 87

EDUCATION & RESOURCES**Associations & Societies**

Assoc of American Ceramic Component Manufacturers (AACCM) OH
 Brick Industry Assn VA
 Glass Mfg Industry Council OH
 Indian Ceramic Society India
 International Centre for Diffraction Data PA
 Journal of the American Ceramic Society OH
 SAMPE CA
 The American Ceramic Society OH

Books

APC International Ltd PA
 Bharat Heavy Electricals Ltd India
 Journal of the American Ceramic Society OH
 SAMPE CA
 Sheffield Pottery MA

Continuing Education

Alfred University NY See ad on page 40
 Arizona State University AZ
 CelSian Glass & Solar BV The Netherlands
 Fraunhofer Institute for Ceramic Technologies and Systems IKTS Germany
 International Centre for Diffraction Data PA
 Jenike & Johanson Inc MA

JTF Microscopy Services LLC NY
 Spontaneous Materials CO
 Tethon 3D NE

Degree Programs, ABET Accredited

Alfred University NY

See ad on page 40



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Case Western Reserve University OH
 Massachusetts Inst of Technology MA
 Missouri University of Science and Technology MO
 Rensselaer Polytechnic Inst NY

Degree Programs, Ceramic



Alfred University NY See ad on page 40
 Fraunhofer Institute for Ceramic Technologies and Systems
 IKTS Germany
 Massachusetts Inst of Technology MA
 Missouri University of Science and Technology MO

Degree Programs, Glass Engrg Science



Alfred University NY See ad on page 40
 Fraunhofer Institute for Ceramic Technologies and Systems
 IKTS Germany

Degree Programs, Materials Science

Alfred University NY See ad on page 40
 Arizona State University AZ
 Case Western Reserve University OH
 Fraunhofer Institute for Ceramic Technologies and Systems
 IKTS Germany
 Massachusetts Inst of Technology MA
 Missouri University of Science and Technology MO
 Rensselaer Polytechnic Inst NY

Employment Services

SAMPE CA

Publications

American Ceramic Society Bulletin OH
 American Scientific Publishers CA
 Chemical Abstracts Service OH
 GrainBound LLC PA
 Indian Ceramic Society India
 Journal of the American Ceramic Society OH

Ultrasonic Transducers

Piezo by Graco OH

■ ELECTRICAL/ELECTRONIC CERAMICS

Antennas, Dielectric

Euro Support Advanced Materials The Netherlands
 O'Keefe Ceramics Inc CO
Trans-Tech Inc a subsidiary of Skyworks Solutions Inc MD See ad on page 81

Capacitors

Associated Ceramics & Technology Inc PA
 AVX Corp SC
 Euro Support Advanced Materials The Netherlands
 Induceric Canada
 Murata Manufacturing Co Ltd Japan

Ceramic-Brazed Assemblies

AdTech Ceramics TN
 CeramTec North America Corp SC
 Induceric Canada
 Morgan Technical Ceramics Auburn CA
 Precision Ferrites and Ceramics Inc CA

Conductors

AdTech Ceramics TN
 CerPoTech AS Norway
 ESL ElectroScience PA
 Master Bond Inc NJ
 NorECs AS Norway

Crystals

Induceric Canada
 Kyocera International Inc CA
 Momentive Performance Materials Inc NY
 MSE Supplies AZ
TevTech LLC MA See ad on page 89

Dielectrics

AVX Corp SC
 Centerline Technologies MA
 CerPoTech AS Norway
 ENrG Inc NY
 ESL ElectroScience PA
 Euro Support Advanced Materials The Netherlands
 Gwent Electronic Materials Ltd UK
 Morgan Advanced Materials CA
 NGK Spark Plug Co Ltd Japan
 Pacific Ceramics Inc CA
 Advanced Ceramic Technology CA

Ferrites & Ferromagnetics

Ferro Ceramic Grinding Inc MA
 Pacific Ceramics Inc CA
 Precision Ferrites and Ceramics Inc CA
 Spontaneous Materials CO

Filters, Dielectric

CerPoTech AS Norway
 Euro Support Advanced Materials The Netherlands
 Murata Manufacturing Co Ltd Japan
Trans-Tech Inc a subsidiary of Skyworks Solutions Inc MD See ad on page 81

Fuel Cells, Solid Oxide

AdTech Ceramics TN
 Associated Ceramics & Technology Inc PA
 Bharat Heavy Electricals Ltd India
 Cancarb Limited Canada
 CerPoTech AS Norway
 ENrG Inc NY
 ESL ElectroScience PA
 Euro Support Advanced Materials The Netherlands
 Gwent Electronic Materials Ltd UK
 Morgan Technical Ceramics Auburn CA

Nexceris LLC OH
 NorECs AS Norway
Trans-Tech Inc a subsidiary of Skyworks Solutions Inc MD See ad on page 81

High-Voltage Insulators

Akron Porcelain & Plastics Co OH
 Bharat Heavy Electricals Ltd India
 Ceramco Inc NH
 CeramTec North America Corp SC
 Du-Co Ceramics Company PA
 Elcon Precision LLC CA
 Morgan Technical Ceramics Auburn CA
 Precision Ferrites and Ceramics Inc CA
 Xiamen Innovacera Advanced Materials Co Ltd China

Hybrid Circuits & Packages

AdTech Ceramics TN
 AVX Corp SC
 Precision Ferrites and Ceramics Inc CA
 Xiamen Innovacera Advanced Materials Co Ltd China

IC Packages

AdTech Ceramics TN
 Kyocera International Inc CA
 NGK Spark Plug Co Ltd Japan

Insulators, Electrical/Electronic

Accuratus Corp NJ
 AdTech Ceramics TN
AdValue Technology LLC AZ See ad on page 51
 Akron Porcelain & Plastics Co OH
 Blasch Precision Ceramics Inc NY
 Ceramco Inc NH
 CeramTec North America Corp SC
 CerCo LLC OH
 Du-Co Ceramics Company PA
 ER Advanced Ceramics Inc OH
 ESL ElectroScience PA
 Federal-Mogul MI
 Ferro Ceramic Grinding Inc MA
 Maryland Ceramic & Steatite Co Inc MD
 Materion Ceramics AZ
 Morgan Technical Ceramics Auburn CA
 NEVZ-Ceramics Close JSC Russia
 P-Ker Engineering NY
 Precision Ferrites and Ceramics Inc CA
 Sonya Ceramics (Export Division) India
 Superior Technical Ceramics Corp VT
 Toto Ltd Japan
 Xiamen Innovacera Advanced Materials Co Ltd China
 Zircoa Inc OH

Magnets

Spontaneous Materials CO

Microwave Packages

AdTech Ceramics TN
 Kyocera International Inc CA
 Precision Ferrites and Ceramics Inc CA

Multilayer Ceramic Capacitors

Euro Support Advanced Materials The Netherlands
 Murata Manufacturing Co Ltd Japan

Multilayer Ceramics, AIN

AdTech Ceramics TN
 NEVZ-Ceramics Close JSC Russia
 Xiamen Innovacera Advanced Materials Co Ltd China

Multilayer Ceramics, Custom

AdTech Ceramics TN
 EBL Products Inc CT

ENrG Inc NY
Euro Support Advanced Materials The Netherlands
Piezo by Graco OH
Xiamen Innovacera Advanced Materials Co Ltd China

Piezoelectrics

APC International Ltd PA
AVX Corp SC
EBL Products Inc CT
Meggit Piezo Technologies IN
Morgan Advanced Materials CA
Sparkler Ceramics Pvt Ltd India

Resistors, Thick-Film

ESL ElectroScience PA
Murata Manufacturing Co Ltd Japan

Resonators

AVX Corp SC
Murata Manufacturing Co Ltd Japan
NGK Spark Plug Co Ltd Japan

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Skyworks Solutions Inc MD**

See ad on page 81

RF Components

AdTech Ceramics TN
Advanced Ceramic Technology CA
Advanced Energy CO
Murata Manufacturing Co Ltd Japan
Precision Ferrites and Ceramics Inc CA

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See ad on page 81

Semiconductors

Cancarb Limited Canada
Elcon Precision LLC CA
Momentive Performance Materials Inc NY
NEVZ-Ceramics Close JSC Russia
Semiconductor Energy Laboratory Co Ltd Japan
Toto Ltd Japan

Sensors

AdTech Ceramics TN
AVX Corp SC
Bullen OH
CeramTec North America Corp SC
EBL Products Inc CT
ENrG Inc NY
Gwent Electronic Materials Ltd UK
Murata Manufacturing Co Ltd Japan
Neoptix Canada
Optocon AG Germany
Piezo by Graco OH
Quality Thermistor Inc ID
Sparkler Ceramics Pvt Ltd India
Technisonic Research Inc CT

Spark Plugs

Associated Ceramics & Technology Inc PA
CerCo LLC OH
Federal-Mogul MI
Gwent Electronic Materials Ltd UK
NGK Spark Plug Co Ltd Japan

Substrates, Alumina

Accuratus Corp NJ

Substrates, Alumina

Actech Precision Ceramic (HK) Limited China
AdTech Ceramics TN
Bullen OH
Centerline Technologies MA
CeramTec North America Corp SC
CoorsTek CO

Du-Co Ceramics Company PA
Ferro Ceramic Grinding Inc MA
Laserage Technology Corp IL
NEVZ-Ceramics Close JSC Russia
NGK Spark Plug Co Ltd Japan
Ortech Inc CA
Saint-Gobain NorPro OH
Toto Ltd Japan
Valley Design Corp MA
Xiamen Innovacera Advanced Materials Co Ltd China

Substrates, Aluminum Nitride

Accuratus Corp NJ
Actech Precision Ceramic (HK) Limited China
AdTech Ceramics TN
Bullen OH
Centerline Technologies MA
CoorsTek CO
Laserage Technology Corp IL
MSE Supplies AZ
NEVZ-Ceramics Close JSC Russia
Ortech Inc CA
Starfire Systems Inc NY
Valley Design Corp MA
Xiamen Innovacera Advanced Materials Co Ltd China

Substrates, Glass

Accuratus Corp NJ
Bullen OH
Centerline Technologies MA
Laserage Technology Corp IL
RISE Research Institutes of Sweden RISE Glass Sweden
Saint-Gobain Recherche France
Valley Design Corp MA

Substrates, Other

Accuratus Corp NJ
Akron Porcelain & Plastics Co OH
Bullen OH
Centerline Technologies MA
CoorsTek CO
Du-Co Ceramics Company PA
ENrG Inc NY
Materion Ceramics AZ
MSE Supplies AZ
NGK Spark Plug Co Ltd Japan

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See ad on page 81

Valley Design Corp MA

Substrates, Silicon Carbide

Bullen OH
Centerline Technologies MA
Ferro Ceramic Grinding Inc MA
Ortech Inc CA
Toto Ltd Japan
Valley Design Corp MA

Superconductors, High-Temperature

ENrG Inc NY
Xiamen Innovacera Advanced Materials Co Ltd China

Tapes

Du-Co Ceramics Company PA
ESL ElectroScience PA
Euro Support Advanced Materials The Netherlands
Haiku Tech Europe BV The Netherlands
Haiku Tech Inc FL
Maryland Ceramic & Steatite Co Inc MD

Thermistors

AVX Corp SC
Gwent Electronic Materials Ltd UK
Murata Manufacturing Co Ltd Japan
Quality Thermistor Inc ID

Transducers

APC International Ltd PA
CSC Force Measurement Inc MA
EBL Products Inc CT
Meggit Piezo Technologies IN
Neoptix Canada
Piezo by Graco OH
Sparkler Ceramics Pvt Ltd India
Technisonic Research Inc CT

Transformers

Grand Power Systems formally Warner Power LLC MI
RoMan Manufacturing MI

Ultrasonic Ceramics

APC International Ltd PA
EBL Products Inc CT
Meggit Piezo Technologies IN
Piezo by Graco OH

Varistors

AVX Corp SC
Kyocera International Inc CA

■ FABRICATING & FINISHING

Abrasives

Allied High Tech Products Inc CA
Diacut Inc CO
Diamond Industrial Tools Inc IL
Dianamic Abrasive Products Inc MI
Dunhua Zhengxing Abrasive Co Ltd China
Dynacut Inc PA
Electro Abrasives Corp NY
Engis Corp IL
FELDCO Intl CA
Jet Edge Waterjet Systems MN
Reade Advanced Materials RI
Saint-Gobain Abrasives MA
Sigmadiamant Spain
Stahl USA Inc WI
Suntech Advanced Ceramics (Shenzhen) Co Ltd China
Washington Mills Electro Minerals Co NY

Brickmaking Equipment

Basic Machinery Co Inc NC
EZG Manufacturing Inc OH
Laeis GmbH Luxembourg
Stedman Machine Co IN

Casting Equipment, Pressure

American Isostatic Presses OH
Cerinnov France
Cerlase France
Dorst America Inc PA
HED Intl Inc NJ
Laguna Clay Co CA
Maryland Ceramic & Steatite Co Inc MD

Casting Equipment, Tape

Haiku Tech Europe BV The Netherlands
Haiku Tech Inc FL
HED Intl Inc NJ

CNC Mills

Elcon Precision LLC CA
Liberty Machinery Co IL
OptiPro Systems LLC NY See ad on page 93
Penn Tool Co NJ
Suntech Advanced Ceramics (Shenzhen) Co Ltd China

Coating Equipment

Allied High Tech Products Inc CA
Cerakote Ceramic Coatings OR

Dynacut Inc PA
Haiku Tech Europe BV The Netherlands
Haiku Tech Inc FL
Liberty Machinery Co IL

Cold-End Coatings, Glass

RISE Research Institutes of Sweden RISE Glass Sweden

Controllers

Dorst America Inc PA
General Glass Equipment Co NJ
Laguna Clay Co CA
Rockwell Automation Inc WI

Cutting Equipment

Basic Machinery Co Inc NC
Diamond Industrial Tools Inc IL
General Glass Equipment Co NJ
Haiku Tech Inc FL
Jet Edge Waterjet Systems MN
Liberty Machinery Co IL
OptiPro Systems LLC NY See ad on page 93
Penn Tool Co NJ
Sigmadiamant Spain
Suntech Advanced Ceramics (Shenzhen) Co Ltd China

Cutting Tools

Diacut Inc CO
Dynacut Inc PA
Engis Corp IL
Jet Edge Waterjet Systems MN
New Tech Ceramics Inc IA
Penn Tool Co NJ
Sigmadiamant Spain

CVD Equipment

Advanced Energy CO
Centorr Vacuum Industries NH
Liberty Machinery Co IL

Deburring Equipment

Engis Corp IL
Liberty Machinery Co IL
Mohr Corp MI See ad on page 79
Penn Tool Co NJ

Diamond Drills

Diamond Industrial Tools Inc IL
Dianamic Abrasive Products Inc MI
Greenlee Diamond Tool Co IL



Mitsubishi Materials Corporation Japan

Diamond Hones

Diamond Industrial Tools Inc IL
Dianamic Abrasive Products Inc MI
Engis Corp IL
Greenlee Diamond Tool Co IL
Saint-Gobain Abrasives MA
Stahli USA Inc WI

Diamond Saw Blades

Allied High Tech Products Inc CA
Aremco Products Inc NY
Comtrust Architectural Mesh Co Ltd China
Diacut Inc CO

Diamond Industrial Tools Inc IL
Dianamic Abrasive Products Inc MI
Dynacut Inc PA
Engis Corp IL
Greenlee Diamond Tool Co IL
LECO Corp MI
Liberty Machinery Co IL
Saint-Gobain Abrasives MA
Texers Technical Ceramics Inc Canada

Diamond Saws

Allied High Tech Products Inc CA
Aremco Products Inc NY
Diacut Inc CO
Dynacut Inc PA
Greenlee Diamond Tool Co IL
Liberty Machinery Co IL

Diamond Tools

Diamond Industrial Tools Inc IL
Dianamic Abrasive Products Inc MI
Engis Corp IL
Greenlee Diamond Tool Co IL
LECO Corp MI



Mitsubishi Materials Corporation Japan
Penn Tool Co NJ
Saint-Gobain Abrasives MA
Sigmadiamant Spain

Dicing Equipment

Aremco Products Inc NY
Diacut Inc CO
Diamond Industrial Tools Inc IL
Dynacut Inc PA
Liberty Machinery Co IL

Dies

Gasbarre Products Inc PA See ad on page 93
Ram Products Inc OH

Dressing Wheels, Diamond

Diacut Inc CO
Diamond Industrial Tools Inc IL
Dianamic Abrasive Products Inc MI
Dynacut Inc PA
Engis Corp IL
Greenlee Diamond Tool Co IL

Electroplating Equipment

Haiku Tech Inc FL
Liberty Machinery Co IL
Penn Tool Co NJ

Extruders

Advanced Machinery Inc MI
American Art Clay Co Inc IN
Basic Machinery Co Inc NC
Detroit Process Machinery MI
Dorst America Inc PA
Ipsen Ceramics IL
Laguna Clay Co CA
Mohr Corp MI See ad on page 79
North Star Equipment Inc WA
Peter Pugger Mfg Inc CA

Feeders

Ingredient Masters Inc OH See ad on page 101
Isoform Ltd UK
Mohr Corp MI See ad on page 79
Wyssmont Co NJ

Forming Equipment

American Isostatic Presses OH
ARBURG GmbH + Co KG Germany
Dorst America Inc PA
HED INH Inc NJ
Ipsen Ceramics IL
Isoform Ltd UK
Lithoz GmbH NY
Mohr Corp MI See ad on page 79
Quintus Technologies LLC OH
Ram Products Inc OH

Glass Finishing Equipment

General Glass Equipment Co NJ
Liberty Machinery Co IL
Lithoz GmbH NY



OptiPro Systems LLC NY See ad on page 93

Glass Forming Equipment

General Glass Equipment Co NJ

Glass Shear Spray

RISE Research Institutes of Sweden RISE Glass Sweden

Glass Supplies

Ipsen Ceramics IL

Grinders, Centerless

Diamond Industrial Tools Inc IL
Liberty Machinery Co IL
Precision Ferrites and Ceramics Inc CA
Suntech Advanced Ceramics (Shenzhen) Co Ltd China

Grinders, Cylindrical

Diamond Industrial Tools Inc IL
Liberty Machinery Co IL
Suntech Advanced Ceramics (Shenzhen) Co Ltd China

Grinders, Finished Product

DCM Tech MN
Ipsen Ceramics IL
Liberty Machinery Co IL
OptiPro Systems LLC NY See ad on page 93
Stahli USA Inc WI

Grinding Wheels

Allied High Tech Products Inc CA
Diacut Inc CO
Diamond Industrial Tools Inc IL
Dynacut Inc PA
Engis Corp IL
Greenlee Diamond Tool Co IL
Penn Tool Co NJ
Sigmadiamant Spain
Stahli USA Inc WI

Hydraulic Systems

Isoform Ltd UK
Ram Products Inc OH

Injection-Molding Equipment

ARBURG GmbH + Co KG Germany
Goceram AB Sweden

Mohr Corp MI

See ad on page 79

Rockwell Automation Inc WI

Suntech Advanced Ceramics (Shenzhen) Co Ltd China

Jigging Equipment

Cerinnov France
Ram Products Inc OH

Lapping Equipment

Allied High Tech Products Inc CA
Diamond Industrial Tools Inc IL

Dynacut Inc PA

Engis Corp IL

Liberty Machinery Co IL

OptiPro Systems LLC NY

See ad on page 93

Sigmadiamant Spain

Stahli USA Inc WI

Lapping Supplies

Allied High Tech Products Inc CA
Diamond Industrial Tools Inc IL
Dunhua Zhengxing Abrasive Co Ltd China
Engis Corp IL
FELDCO Intl CA
Stahli USA Inc WI

Laser Scribes

Centerline Technologies MA
Cerlase France
Lasera Technology Corp IL

Machining Equipment

Dynacut Inc PA
Ferro Ceramic Grinding Inc MA
International Ceramic Engineering MA
Liberty Machinery Co IL
OptiPro Systems LLC NY
Penn Tool Co NJ
Stahli USA Inc WI

See ad on page 93

Mandrels, Diamond

Diacut Inc CO
Diamond Industrial Tools Inc IL
Dianamic Abrasive Products Inc MI
Engis Corp IL
Greenlee Diamond Tool Co IL

Molds, Case

Petro Mold Company PA
Ram Products Inc OH

Molds, Ceramic-Forming

Akron Porcelain & Plastics Co OH
Cerinnov France
Cerlase France
Goceram AB Sweden
Ipsen Ceramics IL
Isoform Ltd UK
Laeis GmbH Luxembourg
Laguna Clay Co CA
Petro Mold Company PA
Ram Products Inc OH
Viridis3D LLC MA

Molds, Models

Petro Mold Company PA
Ram Products Inc OH
Viridis3D LLC MA



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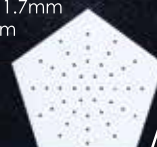
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Plasma Etching Systems

Advanced Energy CO
Liberty Machinery Co IL

Pneumatic Systems

Cyclonaire Corp NE
Ingredient Masters Inc OH
Ram Products Inc OH
Young Industries Inc PA

See ad on page 101

Polishing Equipment

Allied High Tech Products Inc CA
Diamond Industrial Tools Inc IL
Dynacut Inc PA
Engis Corp IL
LECO Corp MI
Liberty Machinery Co IL
OptiPro Systems LLC NY
Penn Tool Co NJ
Sigmadiamant Spain
Stahli USA Inc WI

See ad on page 93

Polishing Powder & Supplies

Baikowski Malakoff Inc NC
C&L Development Corp CA
Dianamic Abrasive Products Inc MI
Engis Corp IL
Sigmadiamant Spain
Stahli USA Inc WI

Presses, Compacting

Detroit Process Machinery MI
Digital Press Inc PA
Dorst America Inc PA
Gasbarre Products (PTX Pentronix) PA

See ad on page 93



Gasbarre Products Inc PA
Mohr Corp MI
Quintus Technologies LLC OH

See ad on page 93
See ad on page 79



Trans-Tech Inc a subsidiary of
Skyworks Solutions Inc MD

See ad on page 81

Presses, Dry

Aadvanced Machinery Inc MI
Dorst America Inc PA

Gasbarre Products Inc PA
Maryland Ceramic & Steatite Co Inc MD
Suntech Advanced Ceramics (Shenzhen) Co Ltd China

See ad on page 93

Presses, Extrusion

Dorst America Inc PA
Maryland Ceramic & Steatite Co Inc MD
Mohr Corp MI
Peter Pugger Mfg Inc CA

See ad on page 79

Presses, Hot

American Isostatic Presses OH
Centorr Vacuum Industries NH
FCT Ingenieurkeramik GmbH Germany
FCT Systeme GmbH Germany
Materials Research Furnaces Inc NH
Oxy-Gon Industries Inc NH
Refrac Systems AZ

See ad on page 85

Presses, Hot Isostatic

American Isostatic Presses OH
AVS Inc MA
FCT Ingenieurkeramik GmbH Germany
Quintus Technologies LLC OH

Presses, Hydraulic

Aadvanced Machinery Inc MI
ARBURG GmbH + Co KG Germany
AVS Inc MA
Digital Press Inc PA
Dorst America Inc PA
Gasbarre Products Inc PA
Laeis GmbH Luxembourg
Materials Research Furnaces Inc NH
Mohr Corp MI
Ram Products Inc OH

See ad on page 93

See ad on page 79

Presses, Isostatic

Aadvanced Machinery Inc MI
American Isostatic Presses OH
Cerinov France
Cerlase France
Detroit Process Machinery MI
Dorst America Inc PA
Gasbarre Products (PTX Pentronix) PA

See ad on page 93



Gasbarre Products Inc PA
Haiku Tech Europe BV The Netherlands
Haiku Tech Inc FL
Isoform Ltd UK
Mohr Corp MI
Quintus Technologies LLC OH
RocCera LLC NY
Suntech Advanced Ceramics (Shenzhen) Co Ltd China

See ad on page 93

See ad on page 79

Presses, Other

ARBURG GmbH + Co KG Germany
Isoform Ltd UK

Presses, Pressure Casting

Cerlase France
Dorst America Inc PA
Peter Pugger Mfg Inc CA
Ram Products Inc OH

Presses, Refractory Shapes

Laeis GmbH Luxembourg

Presses, Rotary

Aadvanced Machinery Inc MI

Presses, Rotary

Materials Research Furnaces Inc NH

Presses, Tile (Ceramic)

Laeis GmbH Luxembourg
Peter Pugger Mfg Inc CA

Pug Mills

Aadvanced Machinery Inc MI
Basic Machinery Co Inc NC
Dorst America Inc PA
Mohr Corp MI
Peter Pugger Mfg Inc CA
Sheffield Pottery MA
Young Industries Inc PA

See ad on page 79

PVD Equipment

Liberty Machinery Co IL
Teeter Marketing Services LLC FL

Roofing Tile Machinery

Laeis GmbH Luxembourg

Setting Equipment

Basic Machinery Co Inc NC

Slab Rollers

North Star Equipment Inc WA

Spray Booths

Treibacher Industrie AG Austria

Sputtering Equipment

Advanced Energy CO
FCT Ingenieurkeramik GmbH Germany

Superabrasives

Diamond Industrial Tools Inc IL
Dynacut Inc PA
Engis Corp IL
Greenlee Diamond Tool Co IL
Liberty Machinery Co IL
Teeter Marketing Services LLC FL

Surface Modification Systems

Teeter Marketing Services LLC FL

Tilemaking Equipment

Basic Machinery Co Inc NC
Peter Pugger Mfg Inc CA
Ram Products Inc OH

Tools, Modeling

Sheffield Pottery MA
Viridis3D LLC MA

Turning Machines, Insulator

Liberty Machinery Co IL

Ultrasonic Machining Equipment

Bullen OH
International Ceramic Engineering MA
Liberty Machinery Co IL



OptiPro Systems LLC NY

See ad on page 93

Used Equipment

Aadvanced Machinery Inc MI
Basic Machinery Co Inc NC
Cerinov France
Diamond Industrial Tools Inc IL
Dorst America Inc PA
Dynacut Inc PA

Liberty Machinery Co IL
Mohr Corp MI
 Ram Products Inc OH
 Viridis3D LLC MA

See ad on page 79

Vibratory Finishing Equipment

Liberty Machinery Co IL
 Penn Tool Co NJ
 Rockwell Automation Inc WI

Weighing/Scales

Optimation - Klug Systems NY

Wheels, Cutoff & Grinding

Diacut Inc CO
 Diamond Industrial Tools Inc IL
 Dianamic Abrasive Products Inc MI
 Dynacut Inc PA
 Engis Corp IL
 Greenlee Diamond Tool Co IL
 LECO Corp MI
 Liberty Machinery Co IL
 Penn Tool Co NJ

Wheels, Diamond

Aremco Products Inc NY
 Diacut Inc CO
 Diamond Industrial Tools Inc IL
 Dianamic Abrasive Products Inc MI
 Dynacut Inc PA
 Engis Corp IL
 Greenlee Diamond Tool Co IL
 LECO Corp MI
 Sigmadiamant Spain
 Stahli USA Inc WI

■ GLASS PRODUCTS

Automotive Glass

Arkema Inc PA
 RISE Research Institutes of Sweden RISE Glass Sweden
 Saint-Gobain Recherche France
 Schott North America Inc NY

Beads/Spheres

Bekeson Glass LLC MS
 Ceradyne Inc a 3M Co KY
 Maryland Ceramic & Steatite Co Inc MD

See ad on page 96



Mo-Sci Corp MO

See ad on page 95

Bioglass

Ceradyne Inc a 3M Co KY



Mo-Sci Corp MO

See ad on page 95

RISE Research Institutes of Sweden RISE Glass Sweden
 Specialty Glass Inc FL

Borosilicate Glass

Bekeson Glass LLC MS
 Bullen OH
 Elan Technology GA
 Garg Process Glass India Pvt Ltd India
 RISE Research Institutes of Sweden RISE Glass Sweden
 Schott North America Inc NY

See ad on page 96



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 Valley Design Corp MA

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 RISE Research Institutes of Sweden RISE Glass Sweden
 Saint-Gobain Recherche France
 Saxon Glass Technologies Inc NY
 Schott North America Inc NY
 Vesuvius SC

Container Glass

Arkema Inc PA
 Cerinnox France
 Owens-Illinois Inc OH
 RISE Research Institutes of Sweden RISE Glass Sweden
 Saint-Gobain Recherche France
 Vesuvius SC

Fibers, Continuous

Saint-Gobain Recherche France
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Fibers, Optical

Adamant Co Ltd Japan

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 Ferro Ceramic Grinding Inc MA
 Imerys Refractory Minerals GA
 RISE Research Institutes of Sweden RISE Glass Sweden
 Valley Design Corp MA

Glass-Ceramics

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 Advanced Ceramic Technology CA
 Arkema Inc PA
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 Bullen OH
 Cerlase France
 Elan Technology GA
 Ivoclar Vivadent Inc Principality of Liechtenstein
 Petro Mold Company PA
 PremaTech Advanced Ceramics MA
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 Texers Technical Ceramics Inc Canada
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 ESL ElectroScience PA
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 Garg Process Glass India Pvt Ltd India
 LECO Corp MI

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HunterLab VA

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Rockwell Automation Inc WI
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B&P Littleford MI
Ceramic Services Inc PA
Cober Muegge LLC CT
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EIRICH Machines Inc IL

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Recco Furnaces CA
Wyssmont Co NJ

Fiberoptic Illuminators

Carl Zeiss Mircolmaging Inc NY

Glass Testing Instruments

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Taber Industries NY

Glassware

AdValue Technology LLC AZ See ad on page 51
Garg Process Glass India Pvt Ltd India
RISE Research Institutes of Sweden RISE Glass Sweden

Glossimeters

Horiba Instruments Inc CA

Hardness Measurement Instruments

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Buehler Ltd IL
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Nanoscience Instruments AZ
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CoorsTek CO
Materion Ceramics AZ
McDaniel Advanced Ceramic Technologies LLC PA
Robocasting Enterprises LLC NM
Xiamen Innovacera Advanced Materials Co Ltd China
Zhengzhou Mission Ceramic Products Co Ltd China

Lab Furnace Tubes

AdValue Technology LLC AZ See ad on page 51
Carbolite Gero UK
McDaniel Advanced Ceramic Technologies LLC PA
Nabertherm Inc DE
Xiamen Innovacera Advanced Materials Co Ltd China
Zhengzhou Mission Ceramic Products Co Ltd China

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L&L Special Furnace Co Inc PA See ad on page 87

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Nanoscience Instruments AZ
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Dalmia Inst of Scientific & Industrial Research India
TA Instruments DE

Microscopes, Interference

Buehler Ltd IL
Carl Zeiss Mircolmaging Inc NY

Microscopes, Other

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Verder Scientific Inc PA

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CSC Force Measurement Inc MA



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H&M Analytical Services Inc NJ
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Harrop Industries Inc OH

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SEMTECH Solutions Inc MA
Technology Assessment and Transfer Inc (TA&T) MD
Technology of Materials CA
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 Detroit Process Machinery MI
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Buckets, Elevator

Optimization - Klug Systems NY

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 Velco GmbH Germany
 Young Industries Inc PA

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Conveyors, Bucket

Applicon Co IN
Ingredient Masters Inc OH

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Conveyors, Pneumatic

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 Carolina Material Technologies NC
 Cyclonaire Corp NE

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 Velco GmbH Germany

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Conveyors, Screw

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 Mixer Systems Inc WI

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Conveyors, Vibrating

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 Carolina Material Technologies NC
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Crushers

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Mohr Corp MI

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Optimation - Klug Systems NY
 Stedman Machine Co IN
 Williams Patent Crusher & Pulverizer Co Inc MO
 Wyssmont Co NJ

Crushers, Hammermill

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Verder Scientific Inc PA
 Williams Patent Crusher & Pulverizer Co Inc MO
 Wyssmont Co NJ

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Crushers, Impact

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 Stedman Machine Co IN
 Williams Patent Crusher & Pulverizer Co Inc MO
 Wyssmont Co NJ

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Crushers, Jaw

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Crushers, Primary

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Crushers, Roll

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 Lancaster Products PA
 Williams Patent Crusher & Pulverizer Co Inc MO

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Dryers, Fluid Bed

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 OPF Enterprises TX
Oxy-Gon Industries Inc NH
 Rockwell Automation Inc WI
 Siemens Process Industries and Drives GA
 Young Industries Inc PA

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Feeders

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 Carolina Material Technologies NC
 Cleveland Vibrator Co OH
 Fritsch GmbH - Milling and Sizing Germany
 Fritsch Milling & Sizing Inc NC
 General Glass Equipment Co NJ
 Jenike & Johanson Inc MA
 Nol-Tec Systems Inc MN
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 Young Industries Inc PA

Feeders, Batch

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Mohr Corp MI See ad on page 79
Netzsch Premier Technologies LLC PA
Wyssmont Co NJ

Grinders

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Diamond Industrial Tools Inc IL
Fluid Energy Processing & Equipment Co PA
Fritsch GmbH - Milling and Sizing Germany
Fritsch Milling & Sizing Inc NC
Glen Mills Inc NJ See ad on page 103
Mohr Corp MI See ad on page 79
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Stedman Machine Co IN
Verder Scientific Inc PA See ad on page 87
Wyssmont Co NJ

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CoorsTek CO
Dunhua Zhengxing Abrasive Co Ltd China
ER Advanced Ceramics Inc OH
Federal-Mogul MI
Fritsch GmbH - Milling and Sizing Germany
Fritsch Milling & Sizing Inc NC
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Jyoti Ceramic Industries Pvt Ltd India
MSE Supplies AZ
Netzsch Premier Technologies LLC PA
Texers Technical Ceramics Inc Canada
Union Process OH
Verder Scientific Inc PA See ad on page 87
Zibo Guangtong Chemical Co Ltd China
Zircor Inc OH

Grinding Mills, Vibratory

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Fritsch Milling & Sizing Inc NC

Gunning Equipment, Refractory

Reed Gunite & Shotcrete Equipment CA
Velco GmbH Germany

Hoppers

Basic Machinery Co Inc NC
Carolina Material Technologies NC
Ingredient Masters Inc OH See ad on page 101
Jenike & Johanson Inc MA
Mixer Systems Inc WI
Optimation - Klug Systems NY
Reed Gunite & Shotcrete Equipment CA

Hydraulic Systems

Basic Machinery Co Inc NC
Ram Products Inc OH

Impeller, Mixing

Lancaster Products PA
Mixer Systems Inc WI

Materials Handling Equipment

Basic Machinery Co Inc NC
Carolina Material Technologies NC
Cyclonaire Corp NE
Gasbarre Products Inc PA See ad on page 93
Lancaster Products PA
Mixer Systems Inc WI
Nol-Tec Systems Inc MN
North Star Equipment Inc WA
Optimation - Klug Systems NY
Penn Tool Co NJ
Reed Gunite & Shotcrete Equipment CA
Rockwell Automation Inc WI
Siemens Process Industries and Drives GA
Tempo Plastic CA
Young Industries Inc PA

Mill Linings

CerCo LLC OH
ER Advanced Ceramics Inc OH
Jyoti Ceramic Industries Pvt Ltd India

Mills

Custom Processing Services PA
ER Advanced Ceramics Inc OH
Euro Support Advanced Materials The Netherlands
Fritsch Milling & Sizing Inc NC
Glen Mills Inc NJ See ad on page 103
Hockmeyer Equipment Corp NC
Netzsch Premier Technologies LLC PA
Raymond Bartlett Snow-Schneck Processing IL
Stedman Machine Co IN
Union Process OH

Mills, Attritor

Advanced Machinery Inc MI
Custom Processing Services PA
Detroit Process Machinery MI
Glen Mills Inc NJ See ad on page 103
Netzsch Premier Technologies LLC PA
Union Process OH
Wyssmont Co NJ

Mills, Ball & Pebble

Advanced Machinery Inc MI
Advanced Ceramics Manufacturing AZ
Detroit Process Machinery MI
ER Advanced Ceramics Inc OH
Fritsch GmbH - Milling and Sizing Germany
Fritsch Milling & Sizing Inc NC
Glen Mills Inc NJ See ad on page 103
Haiku Tech Europe BV The Netherlands
Haiku Tech Inc FL
Mohr Corp MI See ad on page 79
MSE Supplies AZ
Netzsch Premier Technologies LLC PA
Raymond Bartlett Snow-Schneck Processing IL
Union Process OH

Mills, Centrifugal

Fritsch GmbH - Milling and Sizing Germany
Glen Mills Inc NJ See ad on page 103
Verder Scientific Inc PA See ad on page 87

Mills, Hammer

AVEKA MN
Glen Mills Inc NJ See ad on page 103
Stedman Machine Co IN
Verder Scientific Inc PA See ad on page 87
Williams Patent Crusher & Pulverizer Co Inc MO

Mills, Jar

Detroit Process Machinery MI
Fritsch GmbH - Milling and Sizing Germany
Fritsch Milling & Sizing Inc NC

Mills, Jet

AVEKA MN
Fluid Energy Processing & Equipment Co PA
Netzsch Premier Technologies LLC PA

Mills, Planetary

Fritsch GmbH - Milling and Sizing Germany
Fritsch Milling & Sizing Inc NC
Hockmeyer Equipment Corp NC
MSE Supplies AZ
Verder Scientific Inc PA See ad on page 87

Mills, Rod

Wyssmont Co NJ

Mills, Roll

Haiku Tech Europe BV The Netherlands
Haiku Tech Inc FL
MSE Supplies AZ
Raymond Bartlett Snow-Schneck Processing IL
Williams Patent Crusher & Pulverizer Co Inc MO

Mills, Vibratory

Fritsch GmbH - Milling and Sizing Germany
Fritsch Milling & Sizing Inc NC

Mining & Beneficiation Equipment

Netzsch Premier Technologies LLC PA
Reed Gunite & Shotcrete Equipment CA
Rockwell Automation Inc WI
Siemens Process Industries and Drives GA

Mixers, Batch

Carolina Material Technologies NC
Custom Processing Services PA
EIRICH Machines Inc IL



Glen Mills Inc NJ See ad on page 103

Goceram AB Sweden
Lancaster Products PA
Mixer Systems Inc WI
Mohr Corp MI See ad on page 79
Netzsch Premier Technologies LLC PA
Nol-Tec Systems Inc MN
OPF Enterprises TX
Optimation - Klug Systems NY
Peter Pugger Mfg Inc CA

Mixers, Drum

Glen Mills Inc NJ See ad on page 103
Hockmeyer Equipment Corp NC

Mixers, Pneumatic

Carolina Material Technologies NC
EIRICH Machines Inc IL
Nol-Tec Systems Inc MN

Mixers, Portable

Jiffy Mixer Co Inc CA
Mixer Systems Inc WI
Peter Pugger Mfg Inc CA

Mixers, Refractory

Applicon Co IN
B&P Littleford MI
EIRICH Machines Inc IL

EZG Manufacturing Inc OH
 Laeis GmbH Luxembourg
 Lancaster Products PA
 Mixer Systems Inc WI
 Netzsch Premier Technologies LLC PA
 Peter Pugger Mfg Inc CA
 Reed Gunitite & Shotcrete Equipment CA

Mixers, Vacuum

Applicon Co IN
 EIRICH Machines Inc IL
 Netzsch Premier Technologies LLC PA
 Peter Pugger Mfg Inc CA

Mixing Equipment

Aadvanced Machinery Inc MI
 B&P Littleford MI
 Carolina Material Technologies NC
 Custom Processing Services PA
 Detroit Process Machinery MI
 EIRICH Machines Inc IL
 ER Advanced Ceramics Inc OH
 General Glass Equipment Co NJ



Glen Mills Inc NJ See ad on page 103

Goceram AB Sweden
 Hockmeyer Equipment Corp NC
 Laguna Clay Co CA
 Lancaster Products PA
 Mixer Systems Inc WI

Mohr Corp MI See ad on page 79

Netzsch Premier Technologies LLC PA
 OPF Enterprises TX
 Peter Pugger Mfg Inc CA
 Resodyn Acoustic Mixers Inc MT
 Young Industries Inc PA

Nozzles

CerCo LLC OH
 Dunhua Zhengxing Abrasive Co Ltd China
 Maryland Ceramic & Steatite Co Inc MD

Packaging

Tempo Plastic CA

Packaging Equipment

Basic Machinery Co Inc NC

Pneumatic Systems

Applicon Co IN
 Carolina Material Technologies NC
 Cyclonaire Corp NE
 Nol-Tec Systems Inc MN
 Reed Gunitite & Shotcrete Equipment CA
 Velco GmbH Germany
 Young Industries Inc PA

Process Control Equipment

Control Instruments Corp NJ
 Datapaq Inc NH
 General Glass Equipment Co NJ
Ingredient Masters Inc OH See ad on page 101

Nol-Tec Systems Inc MN
 Norcross Viscosity Controls MI
 Optimization - Klug Systems NY
 Ram Products Inc OH
 Rockwell Automation Inc WI
 Siemens Process Industries and Drives GA

Pulverizers

Advanced Machinery Inc MI
 Applicon Co IN
 Basic Machinery Co Inc NC
 Fritsch GmbH - Milling and Sizing Germany
 Fritsch Milling & Sizing Inc NC
Glen Mills Inc NJ See ad on page 103

Mixer Systems Inc WI
 Stedman Machine Co IN
 Williams Patent Crusher & Pulverizer Co Inc MO
 Wyssmont Co NJ

Pumps

ER Advanced Ceramics Inc OH
 Ram Products Inc OH
 Reed Gunitite & Shotcrete Equipment CA

Pumps, Concrete

Reed Gunitite & Shotcrete Equipment CA

Scale Systems

CSC Force Measurement Inc MA
 Mettler-Toledo Inc OH
 Nol-Tec Systems Inc MN
 Optimization - Klug Systems NY

Screens & Screening Equipment

Aadvanced Machinery Inc MI
 Basic Machinery Co Inc NC
 Cleveland Vibrator Co OH
 Control Instruments Corp NJ
 Detroit Process Machinery MI
 Fritsch GmbH - Milling and Sizing Germany
 Fritsch Milling & Sizing Inc NC

Glen Mills Inc NJ See ad on page 103

Midwestern Industries Inc OH

Mohr Corp MI See ad on page 79

Sicco Engineering Works India

Separators

Fritsch GmbH - Milling and Sizing Germany
 Midwestern Industries Inc OH
 Williams Patent Crusher & Pulverizer Co Inc MO

Shredders

Basic Machinery Co Inc NC
 Fritsch GmbH - Milling and Sizing Germany
Glen Mills Inc NJ See ad on page 103
 Stedman Machine Co IN
 Williams Patent Crusher & Pulverizer Co Inc MO

Single-Wafer Packs

Tempo Plastic CA

Size Reduction Equipment

AVEKA MN
 Basic Machinery Co Inc NC
 Custom Processing Services PA
 EIRICH Machines Inc IL
 ER Advanced Ceramics Inc OH
 Fluid Energy Processing & Equipment Co PA
 Fritsch GmbH - Milling and Sizing Germany
Glen Mills Inc NJ See ad on page 103
 Lancaster Products PA
 Netzsch Premier Technologies LLC PA
 Raymond Bartlett Snow-Schneck Processing IL
 Stedman Machine Co IN
 Union Process OH
 Williams Patent Crusher & Pulverizer Co Inc MO
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AVEKA MN
Detroit Process Machinery MI
Dorst America Inc PA
Elan Technology GA
Euro Support Advanced Materials The Netherlands
Mohr Corp MI
Spray Drying Systems Inc MD

See ad on page 79

Storage Equipment

Basic Machinery Co Inc NC

Storage Equipment

Cyclonaire Corp NE

Substrate Wafer Trays

Tempo Plastic CA

Used Equipment

Advanced Machinery Inc MI
American Isostatic Presses OH
Detroit Process Machinery MI
Dorst America Inc PA



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Mohr Corp MI

See ad on page 79

Reed Gunite & Shotcrete Equipment CA

Vacuum Cleaning Systems

Carolina Material Technologies NC

Ventilating Equipment

American Art Clay Co Inc IN

Vibrators

Carolina Material Technologies NC
Cleveland Vibrator Co OH
Optimation - Klug Systems NY
Rockwell Automation Inc WI

Vibrators, Bin

Carolina Material Technologies NC
Cleveland Vibrator Co OH
Cyclonaire Corp NE

Weighing Equipment

Carolina Material Technologies NC
CSC Force Measurement Inc MA
Cyclonaire Corp NE
Mettler-Toledo Inc OH
Nol-Tec Systems Inc MN
Optimation - Klug Systems NY
Rockwell Automation Inc WI
Siemens Process Industries and Drives GA

Weighing/Scales

Optimation - Klug Systems NY

Wire Cloth

Midwestern Industries Inc OH

■ PLANT CONSTRUCTION, DESIGN & ENGINEERING**Brick Production**

Basic Machinery Co Inc NC
Laeis GmbH Luxembourg
Swindell Dressler Intl Co PA

Casting Plants

Dorst America Inc PA
ER Advanced Ceramics Inc OH

Ceramic Production

Cerinnov France
Cerlase France
GrainBound LLC PA
Lucideon UK
Maryland Ceramic & Steatite Co Inc MD
Riedhammer GmbH Germany
Trans-Tech Inc a subsidiary of Skyworks Solutions Inc MD
Viridis3D LLC MA

See ad on page 81

Combustion Systems

Air Products PA
Swindell Dressler Intl Co PA

Decals & Decorating

Cerinnov France
Cerlase France
Gwent Electronic Materials Ltd UK

Drying & Firing

Basic Machinery Co Inc NC
Ceramic Services Inc PA

**Harrop Industries Inc OH**

See ad on page 58

Swindell Dressler Intl Co PA
Wistra GmbH Germany

Electronic Materials Production

Haiku Tech Europe BV The Netherlands
Haiku Tech Inc FL

Trans-Tech Inc a subsidiary of Skyworks Solutions Inc MD

See ad on page 81

Environmental Control

Cyclonaire Corp NE
Mixer Systems Inc WI
Nol-Tec Systems Inc MN
RoboVent MI
Rockwell Automation Inc WI
Saint-Gobain NorPro OH
Tri-Mer Corp MI

Fabrication Shops

Maryland Ceramic & Steatite Co Inc MD

Glass Production

CelSian Glass & Solar BV The Netherlands
General Glass Equipment Co NJ
Optimation - Klug Systems NY
RISE Research Institutes of Sweden RISE Glass Sweden
Schott North America Inc NY
Tri-Mer Corp MI

Inspection Systems

CSC Force Measurement Inc MA
Fosbel Inc OH
Rockwell Automation Inc WI
Siemens Process Industries and Drives GA

Laboratories

Activation Laboratories Ltd Canada

Optical-Fiber Production

Ocean Optics Inc FL

Refractory Production

ER Advanced Ceramics Inc OH
Fosbel Inc OH
Laeis GmbH Luxembourg
Laguna Clay Co CA
Swindell Dressler Intl Co PA

Structural Ceramics Production

CerCo LLC OH
Maryland Ceramic & Steatite Co Inc MD
Swindell Dressler Intl Co PA
Takasago Industry Co Ltd Japan
TevTech LLC MA

See ad on page 89

Tile Production

Laeis GmbH Luxembourg
LIXIL Corporation Japan
Peter Puggler Mfg Inc CA

Whiteware Production

LIXIL Corporation Japan
Ram Products Inc OH
Swindell Dressler Intl Co PA

■ PORCELAIN ENAMEL**Appliances**

Roca Sanitario SA Spain
Zenith China

Architectural Units

Roca Sanitario SA Spain
Zenith China

Ceramic Coatings, Thermal Protection

Cerinnov France
Cerlase France
Trans-Tech Inc a subsidiary of Skyworks Solutions Inc MD
Zenith China

See ad on page 81

Porcelain

Riedhammer GmbH Germany

■ REFRACTORIES

Acid

Allied Mineral Products Inc OH
Magneco Metrel Inc IL
Pacific Refractories Ltd India
Vitcas Ltd UK

Aggregate

Christy Minerals LLC MO
Furnace Products & Services Inc PA
Magneco Metrel Inc IL
Maryland Refractories Co OH

Alumina

Advanced Ceramic Technology CA
Allied Mineral Products Inc OH
Associated Ceramics & Technology Inc PA
Astral Material Industrial Co Ltd China
Baikowski Malakoff Inc NC
Bucher Emhart Glass SA Switzerland
Ceramco Inc NH
CeramTec-ETEC Germany
Dalmia Inst of Scientific & Industrial Research India
Du-Co Ceramics Company PA
Elcon Precision LLC CA
ER Advanced Ceramics Inc OH
Fosbel Inc OH
General Material Industrial Co China
GrainBound LLC PA
IPS Ceramics LTD UK
Ipsen Ceramics IL
Magneco Metrel Inc IL
Maryland Refractories Co OH
Materion Ceramics AZ
Pacific Refractories Ltd India
Pilbrico Company IL
Precision Ferrites and Ceramics Inc CA
Rath Inc DE
Refractory Minerals Co Inc PA
RHI US Ltd NY
Riverside Refractories Inc-Allied Mineral Products AL
Selee Corp NC
Sunrock Ceramics Co IL
Texers Technical Ceramics Inc Canada
Wistra GmbH Germany
Xiamen Innovacera Advanced Materials Co Ltd China
Zircar Refractory Composites Inc NY

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Ipsen Ceramics IL
Merkle International Inc IL

AZS

Bucher Emhart Glass SA Switzerland
Fosbel Inc OH
Magneco Metrel Inc IL
Monofrax LLC NY
RHI US Ltd NY

Backwalls

Fosbel Inc OH
Merkle International Inc IL

Basic

Allied Mineral Products Inc OH
Furnace Products & Services Inc PA
Magneco Metrel Inc IL
RHI US Ltd NY

Blankets

Associated Ceramics & Technology Inc PA
Morgan Thermal Ceramics GA
RHI US Ltd NY
Thermal Products Co Inc GA
Unifrax I LLC NY
Zircar Refractory Composites Inc NY

Boards

Agni Fiber Boards Pvt Ltd India
Morgan Thermal Ceramics GA
RHI US Ltd NY
Saint-Gobain Ceramics & Plastics MA
Thermal Products Co Inc NY
Unifrax I LLC NY



Zircar Ceramics Inc NY
Zircar Refractory Composites Inc NY

Brick

APF Recycling Inc OH
Cancarb Limited Canada
General Material Industrial Co China
HarbisonWalker Intl PA
IFB Insulating Firebrick Inc PA
Morgan Thermal Ceramics GA
Pacific Refractories Ltd India
RHI US Ltd NY
Sunrock Ceramics Co IL
Wistra GmbH Germany

Brick, Acid-Resisting

Pacific Refractories Ltd India
Vitcas Ltd UK

Brick, Fireclay

Allied Mineral Products Inc OH
Alsey Refractories Co MO
Pacific Refractories Ltd India
RHI US Ltd NY
Vitcas Ltd UK

Carbon

Astral Material Industrial Co Ltd China
Cancarb Limited Canada
Pacific Refractories Ltd India
Riedhammer GmbH Germany

Castable

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Cancarb Limited Canada
Capital Refractories Ltd UK
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CONSTRUCTION**

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Magneco Metrel Inc IL
Pacific Refractories Ltd India



Plibrico Company IL See ad on page 105
Plibrico Japan Co Ltd Japan
Reno Refractories Inc AL
RHI US Ltd NY
Riverside Refractories Inc--Allied Mineral Products AL
Selee Corp NC
Vitcas Ltd UK
Zircar Refractory Composites Inc NY

Cements

Allied Mineral Products Inc OH
Aremco Products Inc NY
Capital Refractories Ltd UK
Dalmia Inst of Scientific & Industrial Research India
Furnace Products & Services Inc PA



Gorka Cement Poland See ad on page 71
Kerneos Inc VA
Plibrico Company IL See ad on page 105
Reno Refractories Inc AL
Unifrax I LLC NY
Vitcas Ltd UK

Clay Flux

Furnace Products & Services Inc PA
Peter Puggier Mfg Inc CA
RHI US Ltd NY

Coatings

Allied Mineral Products Inc OH
Aremco Products Inc NY
Elcon Precision LLC CA
Fosbel Inc OH
Furnace Products & Services Inc PA
Fusion Ceramics Inc OH
Gwent Electronic Materials Ltd UK
Induceric Canada
Magneco Metrel Inc IL
Plibrico Japan Co Ltd Japan
Rath Inc DE
Riverside Refractories Inc--Allied Mineral Products AL
Starfire Systems Inc NY
Thermal Products Co Inc GA
Unifrax I LLC NY
Vitcas Ltd UK
Zibo Guangtong Chemical Co Ltd China
Zircar Refractory Composites Inc NY
ZYP Coatings Inc TN

Cordierite

Advanced Ceramic Technology CA
Akron Porcelain & Plastics Co OH
Astral Material Industrial Co Ltd China

CoorsTek CO
Du-Co Ceramics Company PA
ER Advanced Ceramics Inc OH
Industrial Ceramic Products Inc OH
IPS Ceramics LTD UK
Maryland Refractories Co OH
Rauschert Industries Inc GA
Saint-Gobain Ceramics & Plastics MA

Crucibles

AdValue Technology LLC AZ See ad on page 51
Allied Mineral Products Inc OH
APC International Ltd PA
Aremco Products Inc NY
Blasch Precision Ceramics Inc NY
Bucher Emhart Glass SA Switzerland
Ceramco Inc NH
CeramTec-ETEC Germany
Furnace Products & Services Inc PA
Industrial Ceramic Products Inc OH
Ipsen Ceramics IL
LECO Corp MI
Magneco Metrel Inc IL
Materion Ceramics AZ
McDaniel Advanced Ceramic Technologies LLC PA
Progressive Technology Inc CA
Selee Corp NC
Silicon Carbide Products Inc NY
Zhengzhou Mission Ceramic Products Co Ltd China
Zircoa Inc OH

Dead-Burned

Fluid Energy Processing & Equipment Co PA

Fiber Products

Allied Mineral Products Inc OH
Furnace Products & Services Inc PA
LECO Corp MI
Thermal Products Co Inc GA
Unifrax I LLC NY
Vitcas Ltd UK



Zircar Ceramics Inc NY

Filters, Molten Metal

Akron Porcelain & Plastics Co OH
Induceric Canada
Industrial Ceramic Products Inc OH
Selee Corp NC

Foundry

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Blasch Precision Ceramics Inc NY
Capital Refractories Ltd UK
Fosbel Inc OH
Industrial Ceramic Products Inc OH
Ipsen Ceramics IL
LECO Corp MI
Magneco Metrel Inc IL
Plibrico Company IL See ad on page 105
Riverside Refractories Inc--Allied Mineral Products AL
Selee Corp NC
Silicon Carbide Products Inc NY
Zircar Refractory Composites Inc NY

Fused Cast

Fosbel Inc OH
Furnace Products & Services Inc PA
Monofrax LLC NY
Saint-Gobain Ceramics & Plastics MA

Fused Spinel Refractories

Dalmia Inst of Scientific & Industrial Research India

Glass Furnace

Deltech Inc (Deltech Furnaces) CO Inside front cover



Diversified Controls & Systems NY
Fosbel Inc OH
Furnace Products & Services Inc PA
HarbisonWalker Intl PA
Ipsen Ceramics IL
Magneco Metrel Inc IL
RHI US Ltd NY
RISE Research Institutes of Sweden RISE Glass Sweden
Vesuvius SC

Graphite

Applied Ceramics Inc CA
Furnace Products & Services Inc PA
Riedhammer GmbH Germany

Grog

Alsey Refractories Co MO
Maryland Refractories Co OH

Gunning

Allied Mineral Products Inc OH
Blastcrete Equipment Co AL
Capital Refractories Ltd UK
Fosbel Inc OH
Plibrico Company IL See ad on page 105
Plibrico Japan Co Ltd Japan
Reno Refractories Inc AL
Riverside Refractories Inc--Allied Mineral Products AL
Unifrax I LLC NY
Velco GmbH Germany

High-Alumina

Advanced Ceramic Technology CA
Allied Mineral Products Inc OH
Applied Ceramics Inc CA
Astral Material Industrial Co Ltd China
Blasch Precision Ceramics Inc NY
Bucher Emhart Glass SA Switzerland
Ceramco Inc NH
CeramTec-ETEC Germany
Custom Processing Services PA
Dalmia Inst of Scientific & Industrial Research India
ER Advanced Ceramics Inc OH
Fosbel Inc OH
IPS Ceramics LTD UK
Ipsen Ceramics IL
LECO Corp MI
Magneco Metrel Inc IL
Maryland Refractories Co OH
Monofrax LLC NY
Plibrico Company IL See ad on page 105
Plibrico Japan Co Ltd Japan
Precision Ferrites and Ceramics Inc CA
Rath Inc DE
RHI US Ltd NY

Riedhammer GmbH Germany
 Riverside Refractories Inc–Allied Mineral Products AL
 Selee Corp NC
 Sunrock Ceramics Co IL
 Tethon 3D NE
 Xiamen Innovacera Advanced Materials Co Ltd China
 Zhengzhou Mission Ceramic Products Co Ltd China
 Zircar Refractory Composites Inc NY

Insulating Brick

Dalmia Inst of Scientific & Industrial Research India
 Furnace Products & Services Inc PA
 General Material Industrial CoChina
 IFB Insulating Firebrick Inc PA
 Laguna Clay Co CA
 PSH Kilns & Furnaces Canada
 RHI US Ltd NY
 Riedhammer GmbH Germany
 Zircoa Inc OH

Insulation

Agni Fiber Boards Pvt Ltd India
 Capital Refractories Ltd UK
 Du-Co Ceramics Company PA
 Furnace Products & Services Inc PA
 General Material Industrial Co China
 HarbisonWalker Intl PA
 Induceric Canada
Plibrico Company IL
 Plibrico Japan Co Ltd Japan
 PSH Kilns & Furnaces Canada
 Rath Inc DE
 Reno Refractories Inc AL
 RHI US Ltd NY
 Thermal Products Co Inc GA
 Unifrax I LLC NY
 Vesuvius SC
 Wistra GmbH Germany

See ad on page 105



Zircar Ceramics Inc NY
 Zircar Refractory Composites Inc NY



Zircar Zirconia Inc NY

Insulation Board

Agni Fiber Boards Pvt Ltd India
 Thermal Products Co Inc GA
 Unifrax I LLC NY
 Zircar Refractory Composites Inc NY

Insulation Slabs, Calcium Silicate

Furnace Products & Services Inc PA
 Zircar Refractory Composites Inc NY

Insulation Slabs, Vermiculite

IFB Insulating Firebrick Inc PA

Insulation, Microporous

Furnace Products & Services Inc PA
 Thermal Products Co Inc GA
 Unifrax I LLC NY

Kiln Car Insulation

Thermal Products Co Inc GA

Kiln Furniture

Advanced Ceramic Technology CA
 American Art Clay Co Inc IN
 Blasch Precision Ceramics Inc NY
 Ceramco Inc NH
 Induceric Canada
 Industrial Ceramic Products Inc OH
 Ipsen Ceramics IL
 L&L Kiln Mfg Inc NJ
 Laguna Clay Co CA
 Magneco Metrel Inc IL
 Paragon Industries LP TX
 PSH Kilns & Furnaces Canada
 RHI US Ltd NY
 Saint-Gobain Ceramics & Plastics MA
 Saint-Gobain Performance Ceramics & Refractories & Hexoloy SiC Materials MA
 Selee Corp NC
 Silicon Carbide Products Inc NY
 Sunrock Ceramics Co IL
 Texers Technical Ceramics Inc Canada
 Zircar Refractory Composites Inc NY
 Zircoa Inc OH

Magnesite

Allied Mineral Products Inc OH
 Astral Material Industrial Co Ltd China
 Dalmia Inst of Scientific & Industrial Research India
 Fluid Energy Processing & Equipment Co PA
 Furnace Products & Services Inc PA
 RHI US Ltd NY
 Riedhammer GmbH Germany

Monolithic

Allied Mineral Products Inc OH
 Blasch Precision Ceramics Inc NY
 Cancarb Limited Canada
 Ceramco Inc NH
 Furnace Products & Services Inc PA
 Magneco Metrel Inc IL
Plibrico Company IL
 Plibrico Japan Co Ltd Japan
 RHI US Ltd NY
 Riverside Refractories Inc–Allied Mineral Products AL
 Saint-Gobain Ceramics & Plastics MA
 Selee Corp NC
 Zili USA LLC PA

See ad on page 105

Mortars

Allied Mineral Products Inc OH
 Alsey Refractories Co MO
 CoorsTek CO
 Monofrax LLC NY
 Pacific Refractories Ltd India
Plibrico Company IL
 Plibrico Japan Co Ltd Japan
 Refratechnik Ceramics GmbH Germany
 Reno Refractories Inc AL
 RHI US Ltd NY
 Riverside Refractories Inc–Allied Mineral Products AL
 Vitcas Ltd UK

See ad on page 105

Mullite

Advanced Ceramic Technology CA
 Akron Porcelain & Plastics Co OH
 Allied Mineral Products Inc OH

Astral Material Industrial Co Ltd China
 Atlantic Equipment Engineers NJ
 Bharat Heavy Electricals Ltd India
 Bucher Emhart Glass SA Switzerland
 Ceramco Inc NH
 CeramTec-ETEC Germany
 Dalmia Inst of Scientific & Industrial Research India
 ER Advanced Ceramics Inc OH
 Fosbel Inc OH
 General Material Industrial Co China
 Industrial Ceramic Products Inc OH
 IPS Ceramics LTD UK
 Magneco Metrel Inc IL
 McDanel Advanced Ceramic Technologies LLC PA
 Reade Advanced Materials RI
 RHI US Ltd NY
 Robocasting Enterprises LLC NM
 Unifrax I LLC NY

Nozzles

Advanced Ceramic Technology CA
 Blasch Precision Ceramics Inc NY
 Blastcrete Equipment Co AL
 CeramTec-ETEC Germany
 FELDCO Intl CA
 Industrial Ceramic Products Inc OH
 Jyoti Ceramic Industries Pvt Ltd India
 LECO Corp MI
 Magneco Metrel Inc IL
 Reed Gunite & Shotcrete Equipment CA
 Saint-Gobain Performance Ceramics & Refractories & Hexoloy SiC Materials MA
 Silicon Carbide Products Inc NY
 Xiamen Innovacera Advanced Materials Co Ltd China
 Zircoa Inc OH

Paper

Thermal Products Co Inc GA
 Unifrax I LLC NY

Plastic

Allied Mineral Products Inc OH
 Capital Refractories Ltd UK
 Maryland Ceramic & Steatite Co Inc MD
Plibrico Company IL
 Plibrico Japan Co Ltd Japan
 RHI US Ltd NY
 Riverside Refractories Inc–Allied Mineral Products AL

See ad on page 105

Precast Shapes

Allied Mineral Products Inc OH
 Blasch Precision Ceramics Inc NY
 Bucher Emhart Glass SA Switzerland
 Capital Refractories Ltd UK
 Ceramco Inc NH
 CeramTec-ETEC Germany
 Fosbel Inc OH
 Industrial Ceramic Products Inc OH
 Magneco Metrel Inc IL



Plibrico Company IL

See ad on page 105

Plibrico Japan Co Ltd Japan
 RHI US Ltd NY
 Riverside Refractories Inc–Allied Mineral Products AL
 Selee Corp NC
 Silicon Carbide Products Inc NY
 Zircar Refractory Composites Inc NY

Ramming Mixes

Allied Mineral Products Inc OH
 Alsey Refractories Co MO
 Monofrax LLC NY

Pilbrico Company IL**See ad on page 105**

Pilbrico Japan Co Ltd Japan
 RHI US Ltd NY
 Riverside Refractories Inc—Allied Mineral Products AL
 Selee Corp NC

Rods

Actech Precision Ceramic (HK) Limited China

AdValue Technology LLC AZ**See ad on page 51**

Blasch Precision Ceramics Inc NY
 CerCo LLC OH
 Du-Co Ceramics Company PA
 Industrial Ceramic Products Inc OH
 LECO Corp MI
 McDanel Advanced Ceramic Technologies LLC PA
 Saint-Gobain Performance Ceramics & Refractories &
 Hexoloy SiC Materials MA
 Silicon Carbide Products Inc NY

Rollers

Keith Co CA
 Recco Furnaces CA
 Riedhammer GmbH Germany
 Saint-Gobain Performance Ceramics & Refractories &
 Hexoloy SiC Materials MA

Saggers**AdValue Technology LLC AZ****See ad on page 51**

Blasch Precision Ceramics Inc NY
 Ceramco Inc NH
 IPS Ceramics LTD UK
 Ipsen Ceramics IL
 LECO Corp MI
 Magneco Metrel Inc IL
 Selee Corp NC
 Sunrock Ceramics Co IL

Setters**AdValue Technology LLC AZ****See ad on page 51**

Blasch Precision Ceramics Inc NY
 Ceramco Inc NH
 Industrial Ceramic Products Inc OH
 Ipsen Ceramics IL
 LECO Corp MI
 Magneco Metrel Inc IL
 Maryland Ceramic & Steatite Co Inc MD
 Saint-Gobain Performance Ceramics & Refractories &
 Hexoloy SiC Materials MA
 Selee Corp NC
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 semte@asu.edu

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<http://www.aaccm.org>
 kthompson@ceramics.org

AACCM's member companies manufacture components from ceramic powders at U.S. operating facilities. Its purpose is to expand the market for U.S.-manufactured components by enhancing processes and quality and to increase awareness of ceramic applications.

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<http://www.associatedceramics.com>
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Associated Ceramics & Technology Inc is a custom manufacturer of ceramics composed of alumina, steatite, cordierite, spinel, wollastonite, mullite, and high performance materials such as zirconia and yttria-stabilized zirconia. Its engineers' knowledge of the physical and chemical properties of a finished product allow the company to provide excellent quality in applications pertaining to chemical, electrical, wear-resistant, automotive, appliances, and many others. The expansive production capabilities at ACT include more than 155 dry and isostatic presses, seven extrusion presses, 10 kilns, and pre- and post-sintered machining capabilities that are sure to satisfy a customer's every need.

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<http://www.amic.biz>
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AMI produces thermal ceramics, technical ceramics for tile factories, sanitaryware factories, and tableware factories. We also supply to new energy industry, precision casting, chemical industry, and environmental protection industry. We are an ISO9001:2015 certified enterprise. AMI is dedicated to provide products and service with good quality and assist customers with cost.

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 Fax: +1 513-772-9080
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 Cincinnati OH 45215

<http://astromet.com>
 fgorman@astromet.com

Established 1961. Manufacturers precision toleranced advanced ceramic components on a custom order basis per customer design with a focus on wear and corrosion applications. Materials include alumina, zirconia, ZTA, and Macor machinable ceramic.

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<http://micrometals.com>
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Manufactures and distribute high-purity metals, metal powders, oxides, and other compounds to meet the needs and material requirements of the R&D community.

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<https://www.aveka.com>
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<http://ceramcoceramics.com>
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Cerinnov specializes in the manufacturing of production and decoration machines for the ceramic and glass industries: shaping and decorating machines, laser marking, engineering, turn-key plants for tableware, tools, and after sales services.

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Innovnano is a specialist manufacturer of high quality nanostructured zirconia-based powders and alumina zinc oxide (AZO) sputtering targets. Using a unique synthesis technology—emulsion detonation synthesis (EDS)—Innovnano guarantees small grain sizes and excellent chemical homogeneity for high performance powders that support high-tech industries.

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<http://www.iam.kit.edu/km/286.php>
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Scientists in the Institute of Ceramics in Mechanical Engineering within the Faculty of Mechanical Engineering deal with the development of engineering ceramics for various high-tech applications.

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12 Campus Blvd Fax: +1 610-325-9823
Newtown Square PA 19073

<http://www.icdd.com>
marketing@icdd.com

The International Centre for Diffraction Data (ICDD) and Materials Data (MDI) focus on the needs of the materials characterization scientific community by providing the Powder Diffraction File (PDF) and JADE analysis software. PDF Release 2020 contains over 1,000,000 entries for phase identification and JADE Pro software provides the best in X-ray powder diffraction data analysis. These material identification databases are interfaced with diffractometers and data analysis systems of the world's leading software developers and manufacturers of X-ray equipment.

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<http://www.intlceramics.com>

International Ceramic Engineering specializes in the design and manufacture of unique components. Our primary objective is to provide these components and associated services in a manner that ensures consistent and reliable performance. Quality is our commitment to our customers. The quality process is monitored from design to completion to guarantee an integrated and controlled process. This process yields components of the highest precision, accuracy, repeatability and quality. ICE offers a broad range of advanced ceramic and performance plastic materials. Our materials experts are available to help determine the most cost-effective geometry for your advanced material requirements.

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IPS Ceramics is a manufacturer of specialist high-temperature ceramics. Its products are largely based on cordierite-mullite systems that result in aluminosilicate refractory products that are strong and stable at high temperatures.

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<http://ipsenceramics.com>
Ceramics@IpsenUSA.com

Produces a wide variety of standard and custom refractory shapes, and toll firing services. Typical ceramic shapes include plates, saggers, crucibles, and kiln furniture. Formulas include high-percentage alumina and fused silica. Also, toll firing services.

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<http://www.isoform.co.uk>
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Designs and manufactures high-performance dry-bag isostatic presses (CIP), associated tooling, polyurethane molds, powder-filling devices, and unloading systems. A wide range of product shapes can be produced from most free-flowing powdered materials.

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Performs contract and technological research in the field of ceramics and glass. Objective is the development of new products or fabrication technologies. Focus is on solid-state lasers, piezoceramics, ceramic armor, transparent ceramics, and glass.

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Established 1985. R&D-based organization for standardization, quality improvement, and expansion of uses and applications of advanced ceramics, engineering ceramics, and electronic ceramics. Offers contract-basis tests and research.

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MemPro manufactures ceramic nanofibers, polymeric nanofibers, and catalyst products. It continually works with customers to develop and supply new materials for innovative technologies. MemPro produces the highest quality materials backed by unrivaled knowhow.

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Designs and supplies custom suspended refractory systems for glass melting, copper, aluminum, steel pelletizing, and reheat furnaces and incinerators. Manufactures blanket batch charger for glass-melting furnaces.

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Micromeritics materials characterization analytical instruments and contract services determine surface area, porosity, particle size, particle shape, zeta potential, material density, catalytic activity, vapor sorption, powder strength, and more.

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Verity provides manufacturing consulting, technical investigations, analysis, reports, and testimony for the resolution of litigation and claims involving failures of glass and ceramic materials, product liability, and industrial workplace accidents.

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Dillon SC 29536

<http://www.vesuvius.com>
Marcus.Bancroft@vesuvius.com

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<http://www.washingtonmills.com>
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Manufactures fused synthetic minerals for use in refractory raw materials, abrasives, ceramic raw materials, and industrial applications. Products include silicon carbide, brown fused alumina, white fused alumina, boron carbide, bubble alumina, and more.

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<http://www.winnertechnology.co.kr>
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<http://www.unipretec.com>
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Unipretec is a professional manufacturer for advanced ceramics. Our materials include alumina ceramic, zirconia ceramic, boron nitride, and machinable glass ceramic. We aim to provide high quality products and solutions for our customers.

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ZILI USA LLC
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<http://www.zilialutech.com>
jsun@ziliref.com

Zili USA is a subsidiary of Zhejiang Zili Alumina Materials Co Ltd, specializing in high-purity alumina materials development and manufacturing. Its products include tabular alumina, low sodium alumina, reactive alumina, and calcined alumina. With warehouses situated in the states, Zili has fully stocked inventories ready for shipment.

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ZIRCAR CERAMICS INC
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+1 845-651-0441

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<http://zrci.com>
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ZIRCAR Refractory Composites, Inc., produces a comprehensive line of advanced high performance ceramic-ceramic composite materials and related products. Our materials are used around the world in the most demanding thermal, structural and electrical insulating applications ranging in temperatures from 600°C (1,112°F) to 2,200°C (3,992°F). For over thirty years, we have been a problem-solver working with our customers to resolve their thermal management problems. We have developed products that have become industry standards for induction melting, forging and heat treating applications, investment casting, glass processing, hot pressing, and high temperature electrical applications.



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The background of the advertisement features a close-up of a hand wearing a blue nitrile glove, holding a large, clear, curved glass lens. The lighting is dramatic, with a bright light source from the left creating a strong highlight on the edge of the lens and casting the rest into deep shadow. The Corning logo is positioned in the top left corner within a square frame that has a diagonal gradient from light to dark.

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