# Ceramic & Glass MANUFACTURING

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## LEARNING TO FLY: HOW TRAINING AND WORKFORCE DEVELOPMENT ARE CHANGING IN THE ERA OF COVID-19

FLEXIBILITY MATTERS: HIGH PURITY, THIN, FLEXIBLE ALUMINA RIBBON CERAMIC

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# INDUSTRY NEWS

## CORNING EXPANDS GLASS VIAL MANUFACTURING WITH HHS GRANT

Corning Inc. announced it will receive $204 million from the Biomedical Advanced Research and Development Authority (BARDA), part of the Office of the Assistant Secretary for Preparedness and Response at the U.S. Department of Health and Human Services. Under the agreement, Corning will substantially expand its domestic manufacturing capacity of Corning Valor Glass vials to support COVID-19 vaccinations and treatments. Corning will provide priority access to designated BARDA vaccine and drug development partners. The investment will enable Corning to accelerate the scale up of glass tubing and vial manufacturing at three U.S. facilities in Big Flats, N.Y.; Durham, N.C.; and Vineland, N.J.

Corning will expand production at three facilities.

## ARDAGH GROUP SEES INCREASED DEMAND FOR GLASS MILK BOTTLES

Ardagh Group, Glass-North America and Stanpac are providing glass milk bottles to meet increased demand during the coronavirus pandemic. Dairy delivery companies are seeing a surge in demand for glass milk bottles. Ardagh manufactures the American-made glass milk bottles that Stanpac supplies to regional dairy brands. Ardagh Group is a global supplier of recyclable metal and glass packaging and operates 56 metal and glass production facilities in 12 countries. Stanpac is a packaging manufacturer with roots in the dairy industry, providing packaging for milk, ice cream, and other food products. They also provide direct printing on glass containers for wine, beer, spirits, and food containers.

Stevanato Group is a privately owned producer of glass packaging for pharmaceutical companies.

## STEVANATO GROUP PLANS U.S. TECHNOLOGY CENTER

Italy-based Stevanato Group, a producer of pharmaceutical glass containers and drug delivery systems, plans to open its Technology Excellence Center (US TEC) in Boston in September. The center will support biopharmaceutical companies in the selection of glass primary packaging design and technology. US TEC will advise on materials science, chemistry, and engineering, focusing on container closure characterization as well as fill and finish development and optimization. Stevanato Group is one of the world's largest privately-owned designers and producers of glass primary packaging for the pharmaceutical industry.

SiO2 is based in Auburn, Ala.

## SIO2 SCALES UP GLASS VIAL CAPACITY

SiO2 Materials Science announced it scaled its manufacturing capacity for glass vaccine vials ahead of schedule to 400 million doses and is on track to hit 1.2 billion capacity before the end of 2020. Experts have raised concerns about a potential shortage of glass vials needed to deliver a COVID-19 vaccine. In June, the company announced a $143 million investment from the U.S. government to accelerate the production of SiO2's primary packaging platform for storing the vaccines and therapeutics. To support the scaling of its Alabama-based manufacturing campus, SiO2 is investing an additional $160 million, adding two sites to the Auburn campus.

O-I owns five manufacturing plants in Australia and New Zealand.

## O-I PLANS TO DIVEST ITS AUSTRALIA AND NEW ZEALAND UNIT

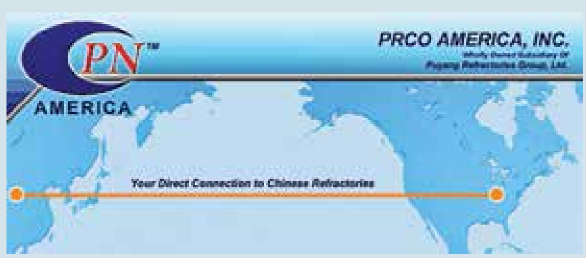
O-I Glass, Inc. agreed to sell its Australia and New Zealand business unit to Visy Industries, a privately owned packaging and resource recovery company. Gross proceeds on the sale and a related sale-leaseback agreement will approximate $947 million. O-I said the sale follows a strategic review of its global portfolio and operating structure. The review is now substantially complete, it said. O-I is the largest manufacturer of glass bottles and containers in Australia and New Zealand, with five manufacturing facilities located in Adelaide, Brisbane, Melbourne, Sydney, and Auckland, and a recycled glass processing plant in Brisbane. Headquartered in Melbourne, the business generated annual sales of $754 million.

## SCHOTT ENTERS INTO MANUFACTURING AGREEMENT WITH LUMUS

SCHOTT manufactures specialty glass, glass-ceramics, and related high-tech materials.

SCHOTT, a manufacturer of optical materials and components for augmented reality (AR) waveguides, agreed to manufacture light-guide optical elements (LOEs) for Israel-based Lumus. The partnership adds a new product line to SCHOTT's offerings to the AR industry. Lumus will handle research and development on the optical design of the reflective waveguides, as well as their commercialization. SCHOTT will make them, using its production network with high-end optical glass melting in Germany, its substrate processing lines in China, and its component factory in Malaysia, where the LOE assembly line is located. SCHOTT AG is headquartered in Mainz, Germany, and is owned by the Carl Zeiss Foundation, one of the oldest private science foundations in Germany.

## PUYANG REFRACTORIES GROUP WILL OPEN ITS FIRST U.S. FACILITY IN 2021




PRCO America Inc., a manufacturer of specialty refractory brick for the steel industry, plans to open its first U.S. production facility next year in Graves County, Ky., a nearly $5.5 million investment. The operation will produce custom-sized, resin-bonded, magnesia graphite refractory brick. The Kentucky Economic Development Finance Authority approved a 15-year incentive agreement with the company, providing up to $550,000 in tax incentives based on the company's investment of $5.49 million and annual targets of creation and maintenance of 32 Kentucky-resident, full-time jobs over 15 years paying an average hourly wage of $24.50, including benefits. PRCO America is a division of Puyang Refractories Group Co. The company's customers include mini-mill and integrated steel producers in the U.S., Canada, and Mexico.

## COLORADO RARE EARTH PILOT PLANT IS COMMISSIONED

A rare earth and critical minerals pilot plant processing facility in Wheat Ridge, Colo., received its required permits, and its pilot plant is now being commissioned. USA Rare Earth, LLC, the funding and development partner of the Round Top Heavy Rare Earth and Critical Minerals Project in West Texas, together with Texas Mineral Resources Corp., made the announcement. The pilot plant is USA Rare Earth's second link in a U.S.-based rare-earth oxide supply chain and will draw on feedstock from the Round Top deposit. With the Round Top project, the processing facility, and the recent acquisition of a neo-magnet plant formerly owned by Hitachi, USA Rare Earth said it has a three-pronged strategy to establish a domestic supply chain for rare earth magnets used in defense applications, wind turbines, electric vehicles, smart phones, medical devices, and 5G networks.

The Round Top rare earths project is located outside El Paso, Texas.

# LEARNING

# HOW TRAINING AND WORKFORCE DEVELOPMENT ARE CHANGING IN THE ERA OF COVID-19

By David Holthaus

Building and maintaining a pipeline of talented and qualified workers was always a priority for manufacturers. Cultivating a skilled workforce able to adapt to changing technical needs is critical to staying competitive and continuing to grow.

Always a challenge, finding and training qualified engineers and others who can thrive in high-tech manufacturing environments became significantly more difficult over the past few months with the spread of the coronavirus SARS-CoV-2 and the COVID-19 disease around the world.

The hands-on experience so essential to training the manufacturing workforce suddenly became something to avoid as schools and workplaces closed, limits on gatherings were advised, and physical distancing became the norm.

The need for qualified talent never stopped, however, and now colleges, technical institutes, employers, and others are figuring out how to nurture the talent pipeline in the era of COVID-19.

For all of them, it's been an exercise in adapting on the fly to a problem they have never encountered before and being prepared to revise plans as conditions change.

Corning Inc. traditionally maintained a strong internship program, with 60 to 80 interns a year, composed of both graduates and undergraduates, just in its research, development, and engineering areas, says Eduardo Bascaran, the lead human resources manager for those business units.

Eduardo Bascaran
Corning Inc.

Those units also developed a co-op program, employing five students every quarter. In the spring, the co-op program came to a halt, and internship offers had to be rescinded, as they were at so many other employers.

The loss of these opportunities, even temporarily, will affect how Corning evaluates prospective employees, Bascaran says.

# TO FLY

When the COVID-19 pandemic hit, Missouri S&T students designed and 3D printed face masks for local health care providers and first responders. *Credit: Missouri University of Science and Technology*

"A lot of our research and development and engineering work involved hands-on experience, and general experience with processing and characterization of glasses and ceramics," Bascaran says. Without that experience, "It's more difficult to assess whether a person has the potential for hands-on work in the laboratory," he says. "We do believe this is going to have an impact. It's really a lost opportunity."

Richard Brow
Missouri S&T

While employers like Corning are becoming reconciled to new workforce conditions that changed almost overnight, engineering schools are also adjusting on the fly to new safety guidelines and requirements while trying to continue to meet the ever-evolving needs of those employers.

One of the hallmarks of the ceramics engineering program at Missouri University of Science and Technology is the hands-on experiences that both undergraduate and graduate students receive.

"They make the powders, consolidate materials, they know how to make glass," says Richard Brow, a longtime professor of ceramic engineering at Missouri S&T. "When they go off to internships or co-ops with companies, our kids are ready to contribute because they've had these experiences."

Graduates of the Bachelor of Science program in ceramic engineering typically go to work at ceramic manufacturers such as O-I or Kohler, or at companies that use ceramic materials in their products, such as GE or Caterpillar.

The laboratory experience at Missouri S&T and elsewhere had to change radically in the spring. In Brow's glass class in March, he asked graduate students to walk through the lab exercises and had them videotaped and made available to undergrads. However, "Looking at a computer screen is a heck of a lot different than putting on protective equipment and going in a furnace and pulling out molten material and making a glass," Brow says. "You need that physical experience to fully understand a process."

## Improve your materials science knowledge with an ACerS short course

The American Ceramic Society offers a series of short courses online that expand on foundational topics and are geared to engineers, scientists, operations professionals, and students looking to improve their materials science knowledge. Go to www.ceramics.org/courses for details on these courses:

- Introduction to Ceramic Science, Technology, and Manufacturing
- Drying of Ceramics
- Introduction to Refractories
- Glaze Manufacturing for Industry
- Firing of Ceramics
- Fundamentals of Industrial Glass Melting Processes
- Dispersion and Rheology Control for Improved Ceramic Processing
- Statistical Process Control in Ceramic Processing
- Additive Manufacturing of High-Performance Ceramics
- Glass Corrosion
- Nucleation, Growth and Crystallization in Glasses—Fundamentals and Applications
- Sintering of Ceramics
- Introduction to Machine Learning for Materials Science

Although conditions were still evolving in late summer, Brow says Missouri S&T was planning to run labs in shifts to maintain adequate physical distancing. Students could opt out and take online versions, he says.

Colorado School of Mines also enjoys a reputation as a hands-on materials science engineering school whose graduates have received jobs in the auto industry, aerospace, refractories, semiconductors, as well as at hometown ceramics manufacturer Coorstek in Golden, Colo.

Geoff Brennecka
Colorado School of Mines

Geoff Brennecka, an associate professor and assistant director of the materials science program, is teaching a ceramics class at Mines this school year, and although things were subject to change, was moving ahead with plans to conduct labs on campus and in person.

He said the school is prioritizing the lab experiences by asking instructors to conduct lectures remotely so the labs can remain on campus.

"The hands-on lab stuff, where you really have to get in and work with the equipment that not everybody has in their kitchen or in their garage, we want to make sure as few people are on campus as feasible, so those experiences don't suffer," he says. "It's better to push those things off campus that can be done remotely. That way we can preserve the on-campus environment and experience for the things that can't be done remotely."

He plans to run the labs in shifts so fewer students are present at any one time and distancing can be maintained.

"Our great challenge now is how to we bring that experience to students under conditions that are much different than they were in February," Brow says.

It's a work in progress as conditions are changing rapidly, and school policies and procedures are stressing flexibility and change above all else.

Brennecka says he's mostly concerned about how the experience of working in teams will change as smaller lab sizes and remote, virtual learning become the norm.

Employers, he says, "are always looking for people who have demonstrated that they can work in teams and can solve problems. Those are skills that engineering students develop through the entire experience on campus. It's a much more holistic experience."

"How does the very concept of working in teams change moving forward?" he asked.

That's a question that can't be answered yet, but if virtual meetings and professional interactions become the new normal, today's students will be prepared for that, he says.

"The default is that we're all going to be using the same kinds of tools for that kind of engagement, so the students that come out of here in a couple of years, they're working in Zoom or have been doing that already for years." Brennecka says.

Brow also sees educational value in students and teachers creating virtual experiences. Creating a virtual reproduction of a lab exercise was instructional, he says. "It's an opportunity for us to provide a deeper description of the chemistry and physics that's going on," he says.

"To the kids who can't come back or who don't want to come back, we will have these elements available," he says.


Colorado School of Mines foundry and lab in pre-pandemic times.
*Credit: Colorado School of Mines*

Two-year technical colleges are also dealing with rapid change in how training is delivered to future manufacturing employees. Providing job-specific training remotely was already challenging, and employers are asking for it to be accelerated, says Vicki Maple, vice president of economic development and innovative workforce solutions at Central Ohio Technical College.

"One of the great changes has been: how can very specific training be delivered remotely but also in an accelerated fashion," she says.

"Before, we were looking at one-year certificates and two-year degrees," she says. "Now, we're having to look at hours and weeks where we have to deliver intense training and development programs to advance the labor force to where they need to be."

Maple, who also heads the college's Workforce Development Innovation Center, says employers are also looking for help in identifying people with leadership skills and getting them trained so their careers can advance and step up to more responsible roles at their workplaces. Her organization has provided leadership training to about 800 people just since the pandemic emerged, she says.

The pandemic and the shift to working at home actually created opportunities for professional development. At Corning, with more time available due to no commuting and fewer meetings, experts within the company were willing to volunteer their time to create training opportunities, Bascaran says.

Employees created a glass class that included 14 30-minute sessions over seven weeks that were recorded for later review. Online attendance ranged from 150 to 300 people, and 600 people attended at least one module, he says.

Corning also connected employees to other online development opportunities offered by Massachusetts Institute of Technology and other organizations.

"It was not a grand strategy, we just took advantage of the opportunity," he says.

When the time comes to return to the office, "We may continue to take advantage of those opportunities," Bascaran says.

No one knows when that time may come, but until it does, workforce professionals will continue to adapt to the ever-changing times and needs of employers.


Vicki Maple
Central Ohio Technical College

## A holistic approach to developing a modern manufacturing workforce

This article was first published on the National Institute of Standards and Technology's Manufacturing Innovation blog. It was edited for length. The full version can be found at https://www.nist.gov/blogs/manufacturing-innovation-blog/holistic-approach-developing-modern-manufacturing-workforce.

By Mary Ann Pacelli

The Oregon Manufacturing Extension Partnership's (OMEP) Smart Talent methodology was launched in 2015 to help small and medium-sized manufacturers (SMMs) address workforce challenges with systematic approaches to recruitment, hiring, onboarding, and early career development.

OMEP has used the methodology with 95 organizations, in engagements ranging from 16 weeks to 18 months. It has responded to client needs by expanding the program to become an integrated holistic approach called Workforce Solutions, which includes managerial training, organizational development, and executive leadership.

Smart Talent has been adopted across the MEP National Network by Centers in Hawaii, Montana, Tennessee, and Puerto Rico. Several others are considering the methodology.

Smart Talent was developed to help manufacturers with the increasingly common—and growing—issue of finding talent to replace an aging workforce. Staffing issues often resulted in quality, productivity, and morale issues, according to OMEP consultants Paola Castaldo and Russ Gaylor.

In many cases, SMMs were trying to quickly onboard new employees for productivity's sake. They struggled with developing effective processes and the people skills required for training, often opting for hiring an experienced technical expert. Entry-level turnover was high, and tribal knowledge was difficult to translate to new employees.

The Smart Talent methodology thrived with its end-to-end approach to recruitment and training. Elements included:

- Expanding the prospect pool by rewriting job descriptions to be more attractive to tech-oriented candidates and broadening recruiting outlets.
- Moving the burden of onboard training from team leaders to the staff, which creates more of a knowledge-sharing culture and repeatable process.
- Using proven adult-learning approaches for more structured on-the-job training, which provided more clear career paths.
- Creating a learning culture in the organization.

OMEP has continued to tweak its methodology, working with its partner MEP Centers to develop new processes, apply best practices, and absorb lessons learned. Smart Talent now encompasses the entire lifecycle of an employee and scope of the company, from entry-level positions to organizational alignment. It is customizable and scalable.

Gaylor offered up a current success story in which CabDoor, a cabinet maker in Salem, Ore., was experiencing high attrition for entry-level hires, some of whom were in their first full-time job. New employees were expected to be at an 80% production level by the end of a third shift. Some of them were overwhelmed from the start.

Of those that made it through the onboarding process, only half were completing the competency test to advance to the next level of employment.

In response, OMEP and CabDoor designed a three-day bootcamp for new hires. Half of the group was on the floor learning job duties, while the other half was in a classroom setting learning about the company, its products, compliance issues, and more. The groups changed places at midday. At the end of three days, the integration of new employees was more effective, and 95% of the new hires had passed the measurement test to become eligible for the next job level.

For more information about how the Smart Talent program works, contact Mary Ann Pacelli at mary.pacelli@nist.gov or your local MEP Center.

**ABOUT THE AUTHOR**

Mary Ann Pacelli is acting division chief of Network Learning and Strategic Competitions at NIST's Manufacturing Extension Partnership. Contact Pacelli at mary.pacelli@nist.gov.

# APPLICATION NOTE: BULK BAG WEIGH BATCHING CONTROLS COMPENSATE FOR TERRA COTTA INGREDIENT VARIATIONS

**Bulk bag dischargers and pairs of flexible screw conveyors at the Gladding, McBean site.** *Credit: Gladding, McBean*

Gladding, McBean (Lincoln, California) is a leading manufacturer of terra cotta products. Founded in 1875, the company mines clay from its own reserves and combines traditional methods with modern technology to create roof tiles, floor and paving tiles, clay pipe, ornamental pieces, and architectural elements for buildings.

To streamline batching and mixing of clay blends for different products, the company installed five bulk bag dischargers and five pairs of flexible screw conveyors from Flexicon to automatically deliver weighments of bulk ingredients for blending of clay compounds. The system cut dispensing and weighing time for each batch by half and reduced out-of-spec material and scrap by 95%.

### COMPENSATING FOR RAW MATERIAL VARIATIONS

Clay is a natural material that varies in composition, so the company must determine the ideal ratio of ingredients for various products. "We have to ensure that what we create in the lab will translate to the final material. The only way to accomplish that is to maintain precise control of production," says Joe Parker, operations manager.

The clay is sourced from the company's nearby mine, classified, and loaded into bulk bags at the plant. Crushed, recycled ceramic material called grog is the other major component used in the manufacturing of terra cotta.

To prepare a batch, operators previously retrieved clays and grogs from bins, weighed them on a scale, and transferred them to the mixer using an open trough conveyor.

The new batching system, supplied by Flexicon Corp. (Bethlehem, Pa.), integrates bulk bag dischargers, flexible screw conveyors, and a central weigh hopper, all of which are actuated by programmable controls, also from the supplier. The system enables Gladding, McBean to vary bulk bag discharging, conveying, weighing, and mixing on a batch-by-batch basis according to recipes developed in the lab. A human machine interface (HMI) includes options for automatic or hand-mode operation, as well as setpoints, adjustments, status, start/stop, completion, and other parameters.

Once the recipe is programmed for a batch, each ingredient is conveyed by a flexible screw conveyor from a bulk bag discharger to a central weigh hopper. Load cells supporting the hopper transmit weight gain amounts to the controller, which steps down the conveyor's feed rate to dribble before stopping it once the precise batch weight is gained. The system weighs up to 30 batches per day, with improved accuracy and reduced labor.

### WEIGHING IN ON BATCHING PERFORMANCE

"The versatility of the system makes it cost efficient," says Egidio Modolo, plant manager. "It's a simple, straightforward process, and an efficient way to measure and transfer clay to the blender."

He notes that no maintenance was required in the six months since installation, and that throughout discharging, conveying, and mixing, the enclosed system prevents dusting.

"We can make a small or large batch, and alter the recipe and raw materials," Parker says. "Currently, we have two different clays and three different grogs. We can change that any time."

Microscopically, clay is very abrasive, Parker adds. "It will destroy just about any equipment you use, over time. One of the reasons we chose this system was for simplicity of maintenance due to few moving parts, which should minimize downtime."

Having the system in place, Parker says, "opens up possibilities for other types of products and materials that need the same type of batching accuracy."

# FLEXIBILITY MATTERS: HIGH PURITY, THIN, FLEXIBLE ALUMINA RIBBON CERAMIC

***Corning first showcased this material at the 2019 Ceramic Expo.*

By Chenggang Zhuang, Yan Wang, Ling Cai, Jody Markley, Heather Vanselous, Nikolay Zhelev, Seong-ho Seok, Lanrik Kester, and Michael Badding

Device manufacturers need innovative new materials to develop smarter, faster, and smaller next-generation electronic devices. Corning has invented a new generation of high-performance ceramic substrates in entirely new form factors that can help solve customer problems.

We demonstrate a unique process able to make high-purity, thin, continuous ceramic ribbons with a dense and fine microstructure. The thin form factor enables fast sintering rates. Across a broad composition space, materials such as zirconia, alumina, and silica can be produced.

In this paper, we introduce a high-performance alumina ribbon ceramic (>99.9 % pure, 1.4 μm fine grains, thin, flexible, and large area) and outline the ceramic's key properties; we also discuss process capabilities demonstrated on this new form factor. This product advances electronic devices with low loss, good heat management, and size miniaturization in high speed data communication (e.g., 5G/mmWave, THz), which is especially essential in unconventional curved or conformal design. The thin ceramic substrate supports nonepitaxial thin film growth, in which a sapphire-like attribute is required as well as large size, thinness, and low manufacturing cost.

**FLEXIBLE ALUMINA?**

If any material is thin enough, it can be flexible. But to be useful in high-tech manufacturing, ultrathin materials need to remain durable and stable in processing and end use. It's a tough problem, and Corning solved it with ceramics thin enough to be spooled on a roll.

Manufacturing of thin ceramics is very difficult due to the challenge of suitable shape control. Traditionally, thin ceramics are fabricated through a costly conventional polishing approach, which limits achievable thicknesses and wafer size. Therefore, identifying a cost-effective process capable of producing high-purity, ultrathin ceramics with good shape control would be a significant innovation for thin sheet technical ceramics.

Corning developed a novel fast sintering process, in which a continuous formed green tape is conveyed through a sintering furnace in a continuous fashion to form a continuous sintered ceramic ribbon. It is a high-temperature, short-time sintering approach, which is possible because thin ceramics can tolerate rapid heating and cooling rates. For example, compared to conventional sintering cycles, which may take many hours or even days, the new firing cycle lasts only minutes.

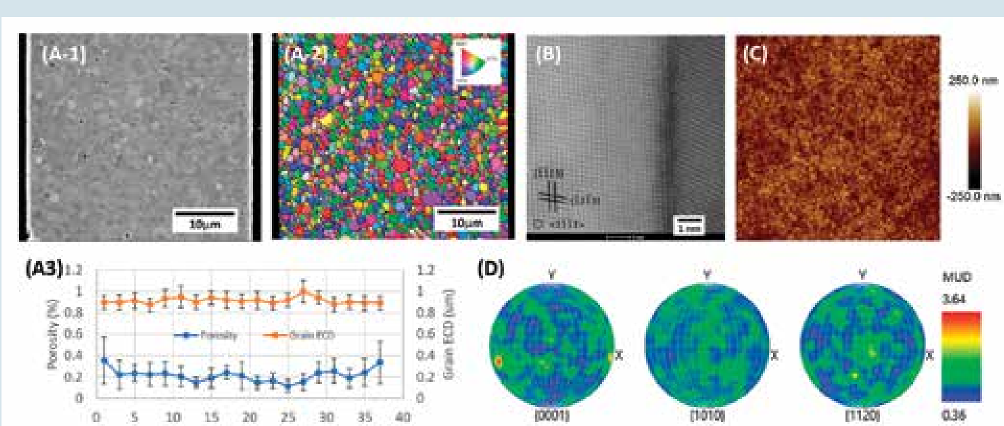



Figure 1. Microstructure of alumina ribbon ceramic. (A) SEM on grain size, porosity; (B) TEM on grain boundary; (C) Atomic force microscopy on surface roughness; (D) Pole figures on grain orientation.
*Credit: Corning, Inc.*

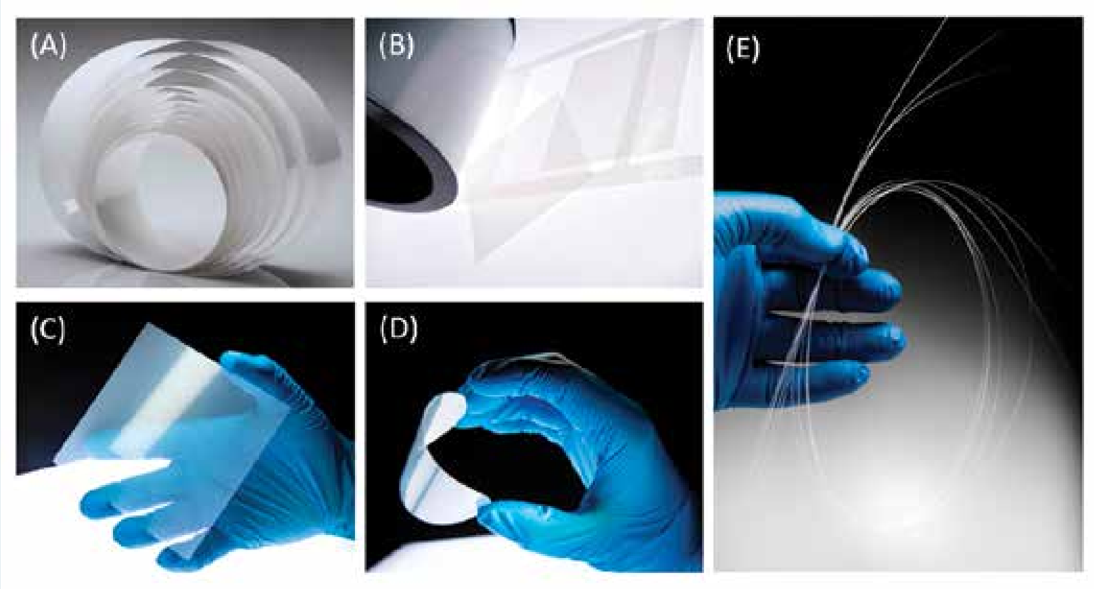



Figure 2. Different form factors of ultrathin alumina ribbon ceramic. (A-B) roll form, (C-D) sheet form/panel, and wafer (E) "cable" form/long narrow strips. *Credit: Corning, Inc.*

This novel sintering process enables several attractive product attributes, including low manufacturing cost and long lengths. Widths of up to 100 mm of spooled alumina were demonstrated for spools up to about 100 m long, and it is potentially scalable to 200 mm or 300 mm width to meet size requirements for most semiconductor wafer processes. Thickness is limited by bend stress and ranges from 20–100 μm for alumina.

**MICROSTRUCTURE**

Compared to conventional sintering, our process favors densification over grain growth in alumina, where high-temperature/short-time sintering enables dense and fine grain microstructures.[1–3]

Figure 1 shows microstructural data collected on the dense and fine-grained features of an alumina ribbon ceramic sample. Image analysis on the cross-sectional electron backscattering diffraction image gives a grain size of about 1.4 μm and SEM porosity of less than 0.4% at pore size of about 190 nm (> 99 % dense), which is also distributed uniformly along the thickness (Figure 1A). Transmission electron microscopy reveals clean grain boundaries with no apparent amorphous film or segregation of impurities (Figure 1B).

As a result of the fine grain, native surface roughness, Ra, retains at 30–50 nm (Figure 1C). This level surface roughness is between typical smooth surface (like glass) and rough surface (like PCB), thus favoring copper adhesion and also enabling fine line structure in metallization processes. Therefore, it should be sufficient for most application cases. Further requirements on surface smoothness (a few nanometers or even less for thin film devices) could be achieved through electropolishing or planarization. Pole figures in Figure 1D proves randomly oriented grain growth and uniform grain size distribution.

**FORM FACTORS**

Alumina ribbon ceramic is produced in rolls (Figure 2A) and supplied as panels or wafers with appropriate cutting (Figure 2B) either through laser or mechanical saw cutting. Figure 2C and 2D show the two most widely used geometries: 100 mm x 100 mm square panels and 100 mm diameter round wafers. The capability of alternative form factors, such as meter-long narrow ribbons, are demonstrated in Figure 2E. This format is unique to thin ribbon ceramics and could be very useful for applications requiring thin, long, and flexible substrates, such as dielec-

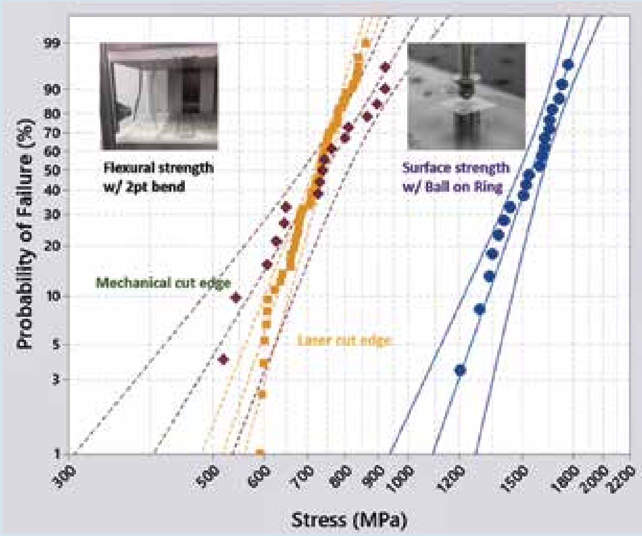



**Figure 3. Surface strength with ball on ring test (blue) and flexural strength with two-point bend (laser edge [yellow] and mechanical cut edge [red]) on 40 µmt alumina ribbon ceramic.** *Credit: Corning, Inc.*

tric waveguides and harsh environment sensors. The example in Figure 2E is a 1 m long strand that is 40 µm thick and 0.5 mm wide. Until now, a long-length, flexible, high-purity alumina ribbon ceramic form factor was not attainable.

## MECHANICAL PROPERTIES

Benefiting from a dense and fine grain microstructure, alumina ribbon ceramic exhibits a high surface strength and edge strength, which could potentially make handling the material easier and less prone to breaking compared to conventionally ground thin-sheet ceramic. Characterizing mechanical properties on thin substrates could be challenging as the sample is too thin and flexible for conventional three- or four-point bend testing. Instead, we combined a ball-on-ring test for surface strength[4] and two-point bend test for flexural strength[5] on 40 µm alumina ribbon ceramic.

The ball-on-ring test[4] provides an "intrinsic" type surface strength measurement while surveying a very small test area, and the two-point bend test is better for evaluating process and handling flaws as it tests a larger area. Figure 3 shows Weibull plots of probability of failure against applied stress in these two different test configurations. A test set with 3 mm diameter stainless steel ball, 4 mm diameter support ring, and 8 mm x 8 mm sample was used for the ball-on-ring test at 1.2 mm/min test speed. The surface strength resulted in a Weibull B10 (10% of probability of failure) of about 1.3 GPa, corresponding to maximum flaw dimension of about 6 µm.

For two-point bend on flexural strength, two sets of samples cut with laser and mechanical saws were tested. While a Weibull B10 of about 600 MPa (and average bend strength of 720 MPa) on laser trimmed edges revealed in the plot indicates edge flaws impact strength, this strength is superior to conventional ground thin-sheet alumina (~400 MPa). Mechanically cut edges show strength about equal to laser trimmed edges with a somewhat wider distribution, indicating alumina ribbon ceramic could accommodate a conventional die cut process.

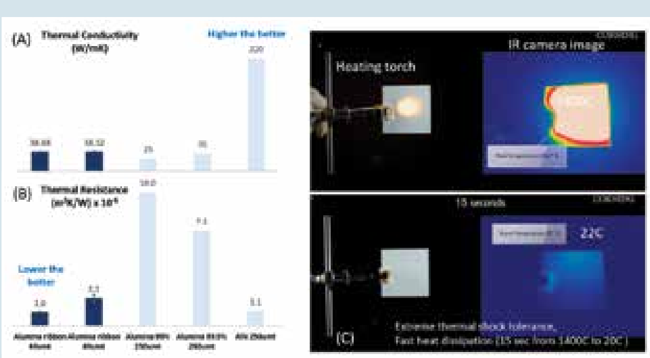



**Figure 4. (A-B) Thermal conductivity and thermal resistance comparison between alumina ribbon ceramic, conventional sheet alumina, and alumina nitride; (C) Illustration of thermal shock tolerance and heat dissipation on 40 µmt alumina ribbon ceramic with a torch experiment.**
*Credit: Corning, Inc.*

## THERMAL PROPERTIES

Many applications take advantage of alumina's good thermal properties. The thermal conductivity of Corning ribbon alumina is 36–38 W/m-K, measured by a hot disc method.[6] Due to its ultrathin thickness, the thermal resistance of 40 µmt alumina ribbon outperforms alumina ceramic of standard thicknesses of 250 µm or more, and it is comparable to a 250 µmt AlN ceramic typically used in situations in which thermal conductivity is paramount, shown in Figure 4A and 4B.

Figure 4C illustrates the extreme thermal shock tolerance and rapid heat dissipation of 40 µm thick alumina ribbon ceramic. Alumina ribbon ceramic can withstand fast local heating over 1,400°C in the center, which would break most thick ceramics as thermal stress accumulates. After removal of the heating source, the body temperature quickly drops to room temperature within 15 second. This attribute could help solve heating problems as high speed, high function integration and device miniaturization becomes an increasing demand in advanced electronics.

## OPTICAL PROPERTIES

Porosity scatters light very effectively, due to the large difference in refractive index between the gas-filled pores and the alumina matrix ($n_{pore}$~1, $n_{alumina}$~1.76). Figure 5 plots total and diffuse transmittance and scatter ratio from UV to near IR wavelength range on a 40 µmt alumina ribbon ceramic specimen for a sample–detector distance of 15 cm. The sample shows about 80% total transmittance in the visible range with a certain level of haze, which is visually illustrated by a set of comparison at zero distance vs. 15 mm between alumina ribbon ceramic and paper underlayment in Figure 5B. Transparency increases as the spectrum moves from visible toward the infrared region.

## ELECTRICAL AND DIELECTRIC PROPERTIES

Alumina is one of the best-known low loss dielectric materials for high frequency signal transmission. In Figure 6A and 6B, the dielectric constant ($D_k$) and dielectric loss ($D_f$) of alumina ribbon ceramic were measured on an Fabry-Perot open cavity[7] from 10 GHz to 60 GHz and com-

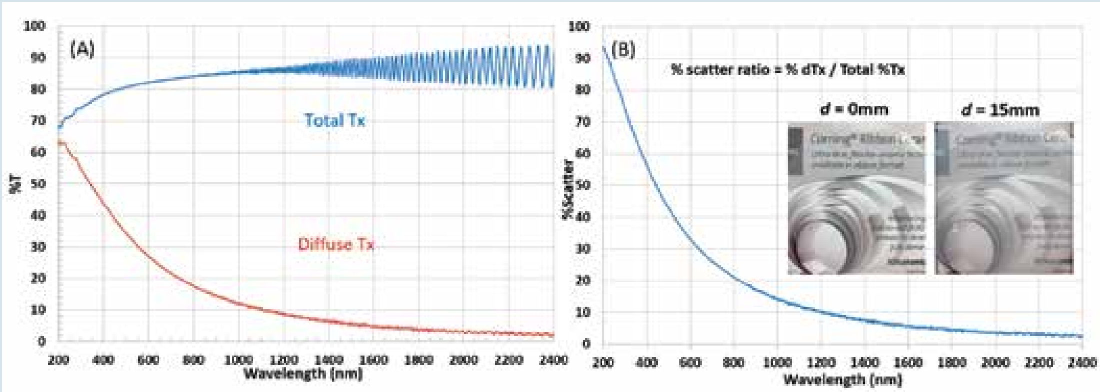



**Figure 5. Transmittance and scattering curve of 40 µm thick alumina ribbon ceramic. Insert picture illustrates high translucency of alumina ribbon ceramics.** *Credit: Corning, Inc.*

pared with commercial alumina ceramics (at different purity levels), fused silica, and one commercial low loss laminate. Because of its high purity and dense microstructure, alumina ribbon ceramics show remarkably low loss tangent ($D_f$ ~ $1x10^{-4}$) across the entire test spectrum, which approaches the accuracy limit of this test method, indicating low dissipation of electromagnetic energy propagation. Coupled with high Dk of about 10, ultrathin alumina could enable device miniaturization and be attractive for a variety of RF devices, for example, compact passive devices, low loss and crosstalk waveguides, and small near-field antennae.

The loss tangent stays almost flat under a test frequency range up to 60 GHz and test temperatures up to 100°C (measured at 10 GHz on a split post resonator, Figure 6C). These properties enable device design across a wide bandwidth and application temperature range.

The DC breakdown voltage/dielectric strength of alumina ribbon ceramic was characterized and plotted in temperature and substrate thickness in Figure 6D (ASTM D149, DC voltage, oil for RT test, air for elevated temp). Alumina ribbon ceramic 40 µmt shows about 10 kV breakdown at room temperature and retains about 5 kV at elevated temperature of 300°C, with performance close to double for 80 µmt substrate at these temperatures (<300°C). These properties could be useful for miniaturization designs of power electronic devices.

## MICROVIAS AND METALLIZATION

Microvias are holes up to 150 µm in diameter, generally laser-drilled, that connect layers in high density interconnect substrates and printed circuit boards. High quality microvia structures can be achieved directly on alumina ribbon ceramic through laser ablation, providing good thermal conductivity while maintaining thinness, which is essential for modern 3D electronics packaging design. Small via size and high via density are achievable on alumina ribbon ceramic at low aspect ratio (AR ~ 2 defined as substrate thickness/average via diameter) because of the material's thinness and good mechanical strength.

Figure 7A shows a 5 x 5 via array at 20 µm via diameter made in 40 µm thick alumina ribbon ceramic (at 400 µm center-to-center pitch), and Figure 7B (at 40 µm center-to-center pitch) corresponds to local via densities of 6 vias/mm$^2$ to 600 vias/mm$^2$. The via is taper shaped with a smooth inner wall, good edge quality, and no microcracks, as shown in Figure 7C and 7D.

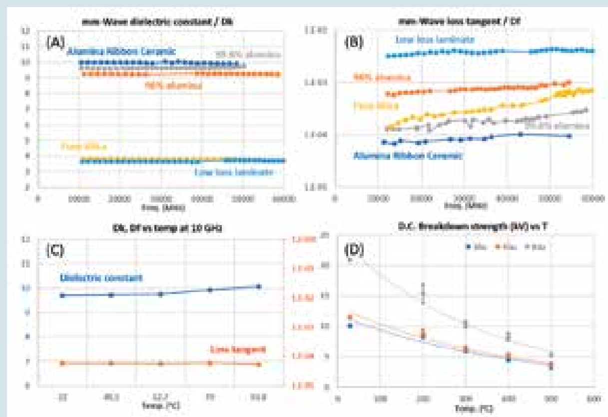



**Figure 6. (A-B) Dielectric constant $D_k$ and loss tangent $D_f$ vs freq. on typical RF low loss materials, ceramics, fused silica and low loss laminate; (C) $D_k$/$D_f$ vs Temp. at 10 GHz for alumina ribbon ceramic; (D) DC breakdown voltage (kV) vs temperature on various thicknesses of alumina ribbon ceramic.** *Credit: Corning, Inc.*

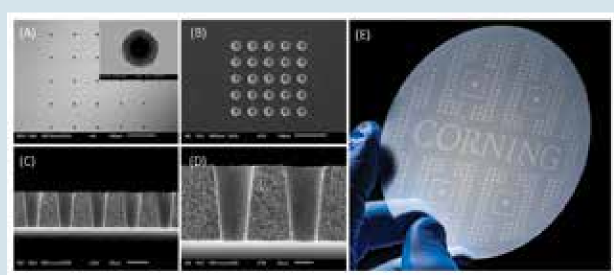



**Figure 7. (A-B) 5x5 20 µm via array at different pitch (400 µm, 40 µm); (C-D) Various via cross sections; (E) Test pattern with about 25,000 40 µm size vias on a 40 µmt 4-inch alumina ribbon ceramic wafer.** *Credit: Corning, Inc.*

Figure 7E is an example of a test via pattern constituting of about 25,000 vias at 40 µm via size and minimal 90 µm center-to-center pitch on a 40 µmt, 100 mm diameter alumina ribbon ceramic wafer.

Metal trace can be achieved by different means on alumina ribbon ceramic. Figure 8A shows a subtractive process for thin film metallization, including sputtered copper (or other metals) with a titanium adhesion layer, and a spin-coat photolithography process to define the pattern. Patterning with minimal 2 µm lines/spacings was demonstrated on 40 µmt alumina ribbon ceramic with a layer of 200 nm sputtered aluminum (SEM image of 5 µm line in Figure 8C). Although not shown here, we also achieved 1.5 µm L/S on 150 nm sputtered copper. Figure 8B shows a semi-additive process for thicker copper metallization, which uses a dry film photoresist for patterning, and the metal layer is built with electroplating process. Figure 8D shows minimal 10 µm lines/spacings achieved on 20 µm plated copper.

Microvias can be metallized either fully filled or conformal coated by choosing appropriate process parameters. Figure 8E gives CT scan images showing high quality via filling is feasible on both of 60 µm opening diameter filled via at 30 µm plated copper and 40 µm opening diameter conformally coated via with 10 µm plated copper. Figure 8F is a double side metallization test pattern with filled via by 20 µmt electroplated copper (minimal L/S: 10 µm); and Figure 8G is another example of aerosol jet printed pattern with 5 µm thick silver at 150 µm line width.

The ability of putting small and high density via and achieving fine line metallization is important to device design with high packaging density.

### FLEXIBILITY AND ROLL TO ROLL PROCESSING

Thinness and flexibility enable flexible or conformal device design. Limiting bend radius is a function of thickness at a given modulus. Figure 9A plots bend stress vs. bend radius for different thickness alumina ribbon ceramic. A 17 mm bend radius on 40 µmt alumina ribbon ceramic yields 500 MPa bend stress on edge. Maximum bending should not exceed this number to avoid fracture, given its 600 MPa flexural edge strength. If using the 50% strength guideline, the recommended bending radius is 35 mm and 70 mm for 40 µmt and 80 µmt alumina ribbon ceramic, respectively, corresponding to 3-in and 6-in roller diameters. Figure 9B shows successful winding of a piece of 15 mm wide and 40 µm thick alumina ribbon ceramic strip on a 1.5-in diameter roller.

Thin flexible alumina ribbon ceramic provides a set of attractive attributes of high-performance technical ceramics; with its unique form factor, it can fit into many unique designs in a broad application space. Potential application includes low loss substrate or waveguide for high speed data communication (from RF to THz), large size flexible sensors for high temperature or harsh environment, thermal management substrate for high power devices (LEDs, VCSELs), flexible heaters, and actuators, among others.

It has been demonstrated that alumina ribbon ceramic is compatible to those key downstream processes. However, as a thin inorganic material, handling could be challenging with current manufacturing processes that are designed around thick substrate. Further process developments, such as temporary bonding to a carrier and/or application to a continuous roll-to-roll process, could alleviate this challenge.

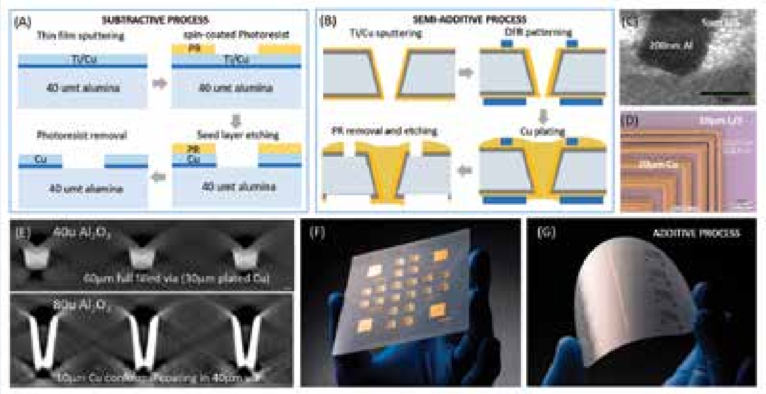



Figure 8. (A-B) Scheme of two photolithography processes for a patterned metallization layer on alumina ribbon ceramics; (C-D) Examples of pattern resolution with process A and B; (E) Via filling and conformal coating; (F) Example of direct plated copper (semi-additive process B); (G) Example of aerosol jet printing (additive process). *Credit: Corning, Inc.*

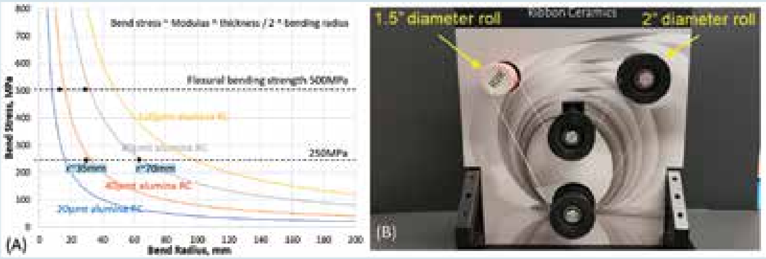



Figure 9. (A) Stress vs. bend radius over different thickness of alumina ribbon ceramic; (B) Example of conveying 40 µmt alumina ribbon ceramic. *Credit: Corning, Inc.*

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