



Technical Ceramics

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TABLE OF CONTENTS

4 ARTICLE
**From Debinding to Silicon Infiltration:
Furnace Requirements Across Non-
Oxide Ceramics Processing**

13 NEWS
**Ultra-Fast Light Control in Transparent
Ceramics Explained**

19 ARTICLE
Ceramics: Oxides vs Nitrides

28 ARTICLE
**Engineering Technical Ceramics
Through Particle Insight**

43 ARTICLE
**Radiation-Resistant Materials: Tough
Space Materials**

49 NEWS
**New Concrete Method Resists Heat,
Chemicals, and Cracking With Nano-
Alumina**

53 ARTICLE
**Advanced Ceramics in the Lab:
Reproducible Size Reduction and
Clean Material Transfer**

69 ARTICLE
**What Makes Gallium Nitride Important
for Power Electronics?**

75 NEWS
**Silicon Carbide Motor Drive Powers
Successful Hybrid Test Flight**



Foreword

Welcome to the latest edition of our Industry Focus eBook, where we explore the dynamic and increasingly vital world of technical ceramics. From extreme-temperature processing to advanced electronics, space materials, and next-generation construction, technical ceramics continue to demonstrate their value across some of the most demanding applications in science and industry.

These materials are prized for their strength, hardness, thermal stability, chemical resistance, and ability to perform where conventional materials fall short.

As industries push for higher efficiency, greater durability, and improved sustainability, ceramics are playing an essential role in enabling innovation across energy, aerospace, manufacturing, research, and infrastructure.

In **From Debinding to Silicon Infiltration: Furnace Requirements Across Non-Oxide Ceramics Processing**, we examine the critical role of furnace technology in producing high-performance non-oxide ceramics, highlighting the precision required at each stage of processing.

Ultra-Fast Light Control in Transparent Ceramics Explained looks at how transparent ceramics are opening new possibilities in photonics and optical technologies, offering exciting potential for rapid light manipulation.

With **Ceramics: Oxides vs Nitrides**, readers can explore the key differences between two important ceramic families and better understand how their properties influence real-world applications.

Engineering Technical Ceramics Through Particle Insight demonstrates how detailed particle analysis supports the design and optimization of ceramic materials, helping manufacturers improve performance and consistency.

In **Radiation-Resistant Materials: Tough Space Materials**, we turn our attention to the demanding conditions of space and the materials capable of withstanding radiation, heat, and mechanical stress.

New Concrete Method Resists Heat, Chemicals, and Cracking With Nano-Alumina highlights how ceramic-based innovation is strengthening construction materials for harsher environments.

Laboratory processing is also explored in **Advanced Ceramics in the Lab: Reproducible Size Reduction and Clean Material Transfer**, which focuses on reliable preparation methods for advanced ceramic research.

Finally, **What Makes Gallium Nitride Important for Power Electronics?** and **Silicon Carbide Motor Drive Powers Successful Hybrid Test Flight** showcase how ceramic semiconductors are transforming power systems, electrification, and aerospace innovation.

This eBook, sponsored by Verder, brings together a wide-ranging view of technical ceramics and their growing influence. As you explore these pages, we invite you to discover how these remarkable materials are helping to solve complex challenges and shape the next generation of industrial innovation.

From Debinding to Silicon Infiltration: Furnace Requirements Across Non-Oxide Ceramics Processing

Thermal processing is a crucial step in the production of advanced technical ceramics, directly establishing microstructural evolution, residual porosity, phase distribution, shrinkage, dimensional stability, and, ultimately, the component's mechanical, thermal, and electrical properties.



Image Credit: Carbolite

This is especially true for non-oxide ceramics, for which exact temperature control must be paired with strict control of atmosphere, pressure, volatile removal, and material compatibility among the load, process chamber, and hot-zone components.

For systems like SiC, C/SiC, reaction-bonded SiC (RB-SiC), recrystallised SiC (RSiC), pressureless sintered SiC (SSiC), Si_3N_4 , AlN, and related materials, there is a narrower process window compared to oxide ceramics.

Small variations in atmospheric composition, residual oxygen level, or temperature consistency may modify surface chemistry, interfere with reactions, influence the behavior of sintering aids, and change phase formation.

The operational challenge is, therefore, not only achieving a specified temperature, but also maintaining a stable, reproducible thermochemical environment that is compatible with the

material system's chemistry.

Debinding, Pre-Treatment, and Volatile Management

Debinding is one of the most sensitive stages of the production process.

In components produced by extrusion, injection molding, pressing, casting, additive manufacturing, or by forming carbonaceous preforms, binders, plasticizers, organic residues, or solvents must be removed at rates suitable with gas diffusion through the green body.

Excessive heating rates or inadequate off-gas removal can cause internal cracking, delamination, uneven porosity, and recondensation of volatiles on colder furnace components.

This cycle often produces water (H_2O), carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), and other organic compounds. In carbon-based systems designed for subsequent liquid silicon infiltration, thermal pre-treatment must maintain an open and interconnected pore structure while avoiding residues that would hamper silicon wetting.

Debinding is particularly important in non-oxide ceramics gasses and residual species have a direct influence on downstream reactions.

Operationally, this stage requires:

- Stable thermal profiles with solid uniformity at low to intermediate temperatures
- Optimized flow passthrough chamber and load for efficient transportation of volatile species
- Defined atmospheres, usually nitrogen gas (N_2) or argon (Ar)
- Implemented exhaust gas management and safety measures



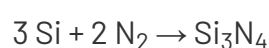
Hot-wall retort furnace for debinding and controlled atmosphere heat treatment. Image Credit: Carbolite

A hot-wall furnace, such as the **Carbolite GLO** operating under a controlled atmosphere, is ideal for these requirements. Integrated gas monitoring, exhaust control, and interlock systems may be necessary - and are available - for safety-critical processes with a high organic load.

Debinding can also be carried out in a high-temperature cold-wall furnace. This enables debinding and subsequent heat treatment to be performed in a single system, reducing additional handling and cool down time. However, the lack of separation between process phases raises the danger of hot zone contamination by binder residues, which must be carefully considered.

Nitride-Bonded SiC: Nitridation and Nitrogen Control

In nitride-bonded silicon carbide (NSiC), bonding is achieved by turning metallic silicon into silicon nitride in a nitrogen atmosphere.



Processing temperatures are normally around 1400 °C, although essential parameters go beyond temperature alone. Nitrogen availability, temperature uniformity, ramp control, and atmospheric purity all have a direct impact on reaction completion and microstructural homogeneity. Residual oxygen is also an important factor, as it can produce surface coatings that inhibit nitridation or alter the intergranular phase.

NSiC components usually require multiple thermal stages, including preliminary debinding under inert gas and, in certain cases, post-treatment in air to form protective surface layers. These phases are often carried out in separate furnaces because the graphite furnaces used for nitridation are incompatible with air operation.



Graphite cold-wall furnace architecture for high-temperature processing under nitrogen and inert gas. Image Credit: Carbolite

Graphite cold-wall furnaces, such as the Carbolite HTK or LHTG, are ideal for nitrogen nitridation because they provide the necessary temperature, homogeneity, and atmospheric control.

RSiC and SSiC: Densification and High-Temperature Processing



Image Credit: Carbolite

The core challenge when using recrystallised SiC (RSiC) and pressureless sintered SiC (SSiC) is managing densification at extremely high temperatures. Following burn out or pre-sintering, RSiC processing necessitates high temperature treatment, usually in a vacuum or inert atmosphere.

SSiC is even more sensitive, as densification is heavily reliant on cycle precision, sintering aid distribution, free carbon content, and precisely controlled dwell time at peak temperature.

At temperatures from 2000–2400 °C, the nominal setpoint temperature alone is not a reliable performance indication. Small fluctuations in spatial temperature can cause considerable differences in shrinkage, grain growth, local porosity, and mechanical property scatter.

Thus, furnace requirements include:

- Uniform temperature distribution
- Reliable temperature measurement with long-term stability
- Controlled dwell time at peak temperatures
- Chamber designs reduce heating element wear at severe temperatures
- Controlled cooling reduces residual strains

Cold-wall **graphite furnaces**, such as the Carbolite HTK, HBO, or LHTG, are ideal for final sintering due to their temperature capabilities, atmospheric control, and thermal stability. Debinding steps can be performed independently in a Carbolite GLO hot wall furnace using inert gas.

SiSiC, RB-SiC, and Liquid Silicon Infiltration



Industrial liquid silicon infiltration setup using bottom-loading graphite furnaces. Image Credit: Carbolite

Liquid silicon infiltration (LSI) is one of the most challenging thermal processes in non-oxide ceramics. Preform capillarity, silicon viscosity, wettability, reaction kinetics, and chamber pressure all interact to determine process behavior.

Typical processing temperatures vary from 1450–1650 °C. The challenge is not just melting silicon, but also maintaining a regulated partial pressure regime that prevents excessive silicon evaporation while allowing adequate mobility for infiltration and reaction.

Operational needs include:

- Effective elimination of volatile species
- Stable and well-controlled partial pressure
- Use of small, well-controlled Ar or N₂ fluxes to protect the system
- Low leakage rate
- Hot zone designs for liquid silicon infiltration commonly use graphite heating systems and retorts to protect the furnace structure from silicon reactions
- Reliable temperature control and measuring

Cold-wall graphite furnaces with retort operation and pressure control, such as the **Carbolite HTBL** or HTK, are suitable for this purpose. To reduce contamination risk and increase process stability, debinding or carbonization should be performed separately from the infiltration stage in most circumstances.

Translating Process Requirements into Furnace Architecture

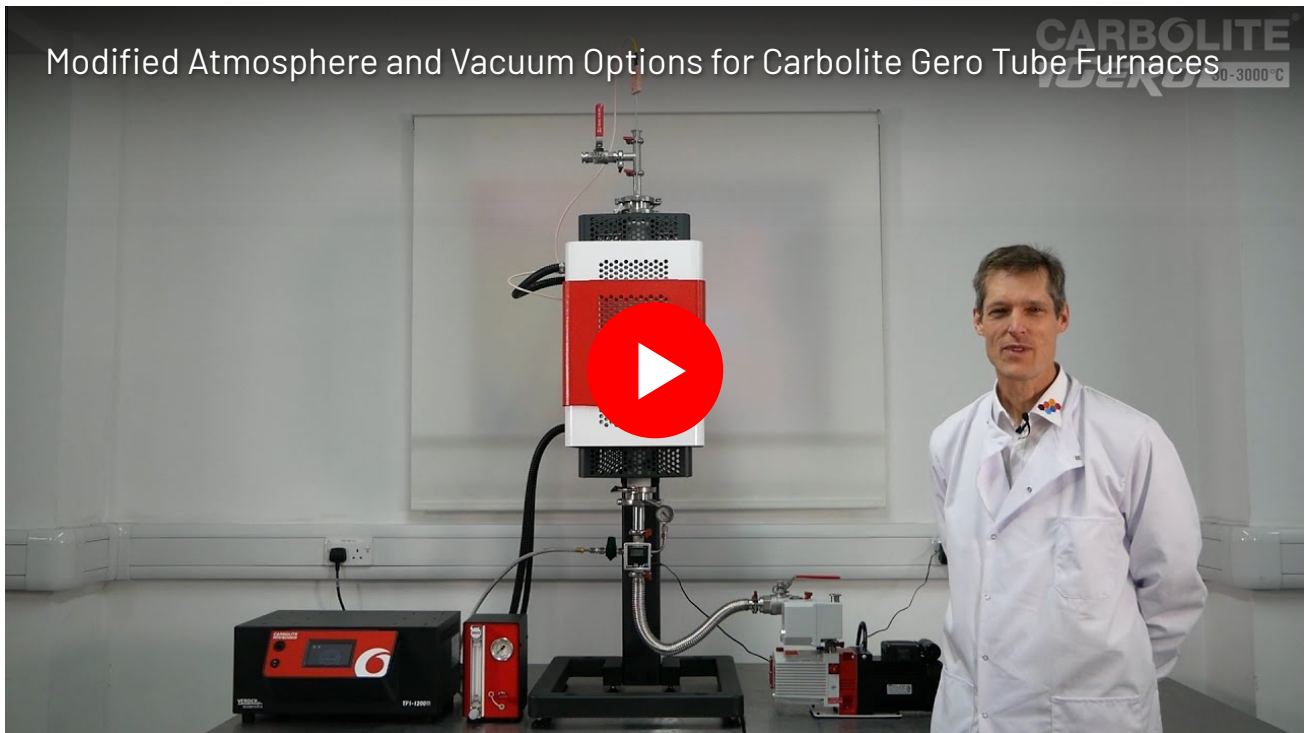
For non-oxide technical ceramics, furnace selection is restricted by a limited range of truly discriminating factors.

1. **Ensure consistent and reliable temperature measurement**, as reactions and densification rely on local temperature rather than controller setpoints.
2. **Maintain thermal process stability**, especially during longer stay stages.
3. **Atmosphere control**, including consistent gas flows, pressure management, and leak tightness
4. **Ensure safe off-gas handling** during debinding and reactive procedures.
5. **Sustain material compatibility** for chamber and hot zone components with nitrogen, argon, vacuum, and reactive species.

In practice, this results in a clear correlation between process step and furnace type:

- **Debinding and pre-sintering under inert gas with high volatile load**: Carbolite GLO hot-wall furnaces.
- **High-temperature reactions and sintering in graphite furnaces under N₂, Ar, or vacuum**: Carbolite HTK, LHTG, and HBO cold-wall furnaces.
- **Liquid silicon infiltration with pressure control and system protection**: Carbolite HTBL or HTK cold-wall furnaces.

- **Laboratory and research and development processes requiring flexible gas configurations:** Carbolite tube furnace ranges (e.g. TS, TF, TSR series), configured for the specific chemistry.



Video Credit: Carbolite

Conclusion

Material behavior when thermally processing non-oxide technical ceramics is determined by a combination of temperature, atmosphere control, pressure, diffusion kinetics, volatile release, and process chemistry compatibility with furnace materials.

Thermal stability, environment control, and exhaust gas handling all affect the final microstructure, as much as the part's composition itself.

Silicon carbide systems are particularly illustrative: reactions, debinding, recrystallization, sintering, and liquid silicon penetration all have separate working windows, but all require careful thermochemical control.

By aligning furnace architecture with the unique requirements of each process stage, material demands may be converted into thermal solutions that are repeatable, stable, and technically

sound.



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Ultra-Fast Light Control in Transparent Ceramics Explained

A new physics theory could explain why transparent ceramics manipulate light far better than existing models predicted.



Study: [Dynamic Atomistic Polar Structure Underpins Ultrahigh Linear Electro-Optic Coefficient in Transparent Ferroelectric Ceramics Image](#). Credit: Andrzej Rostek/Shutterstock.com

The recent research from Penn State has proposed a sophisticated theory that elucidates the reasons behind the exceptional light control capabilities of ceramic materials, potentially paving the way for the large-scale production of these substances for quicker, more compact, and energy-efficient technologies used in high-speed communications, medical imaging, and advanced sensing. The study was published in the *[Journal of the American Chemical Society](#)*.

The novel category of [ceramics](#) is not only transparent but also possesses the ability to manipulate light with remarkable efficiency, surpassing all theoretical predictions.

To address the enigma surrounding the unexpectedly superior electro-optic properties of transparent ceramics – specifically, their capacity to alter the bending or transmission of light

upon the application of voltage – Haixue Yan, a reader in materials science and engineering at Queen Mary University of London, consulted with Zi-Kui Liu, a professor of materials science and engineering at Penn State.

Liu had previously formulated an advanced theory of entropy, which posits that systems tend to move towards disorder in the absence of energy to maintain order. This sophisticated theory, referred to as zentropy theory, integrates quantum mechanics, thermodynamics, and statistical mechanics into a cohesive predictive model.

Collaborating with a team from various institutions across six countries, they found an answer.

Ceramics present significant benefits for optical technologies as they are considerably less expensive to produce compared to single crystals, simpler to scale into functional components, and enable accurate control over composition.

The material needs to be transparent to allow light to pass through seamlessly, a persistent challenge that recent advancements in processing have ultimately addressed for use in electro-optic devices.

“ *Ceramics are much cheaper, easier to manufacture, and allow precise control of the material's chemical composition. The challenge is that ceramics must be transparent, so the light can pass through them smoothly without distortion, before they can function as electro-optic materials.*

Zi-Kui Liu, Professor, Materials Science and Engineering, Penn State

Researchers attained transparency through enhanced manufacturing techniques that eliminate the minute imperfections within the ceramic. These imperfections typically scatter light, resulting in a cloudy appearance of the material. The latest methods facilitate a more uniform alignment of the ceramic's internal grains, significantly reducing defects and permitting light to pass directly through.

The research team employed these techniques to produce the fully transparent ceramics used in the study. Consequently, this led to the unexpectedly strong electro-optic results, which surprised the researchers.

“ There was no existing theory in the ferroelectrics community that could explain these results.

Zi-Kui Liu, Professor, Materials Science and Engineering, Penn State

Liu explained that Yan learned of his zentrophy theory and reached out to collaborate.

Liu stated that the team was inspired by indications found in the scientific literature suggesting that transparent ferroelectric single crystals featuring dense domain walls might exhibit exceptionally strong electro-optic properties.

Researchers theorized that if atypical electro-optic behavior manifested in single crystals characterized by numerous domain walls, the internal boundaries that distinguish differently oriented regions within the material, then the same fundamental mechanism could potentially be observed in ceramics, which inherently possess even more complex domain structures.

Yan, Liu, and their colleagues discovered that a similar mechanism was present, resulting in significantly enhanced performance after examining the transparent ceramic materials. The challenge was to comprehend the underlying reasons.

In standard **ferroelectric materials**, the electric charge is organized into large 'domains,' which are areas composed of thousands of atoms that align and reverse direction collectively when a voltage is applied.

These substantial domains function effectively for technologies that operate at slower, radio-frequency speeds; however, they are unable to respond swiftly enough to the extremely rapid light waves used in photonics. The researchers indicated that large domains could not explain the exceptionally strong electro-optic effects observed in transparent ceramics.

The team used high-resolution transmission **electron microscopy** along with sophisticated computer simulations to examine the material at a significantly smaller scale. The team discovered that the material comprised minuscule pockets of polarization measuring merely a few atoms in width.

These diminutive, rapidly responding structures, akin to "mini-domains," provided insight into the exceptional performance.

“ *These very small polar features have extremely fast relaxation times. They can adjust their electronic polarization almost instantly under an applied field.*

Zi-Kui Liu, Professor, Materials Science and Engineering, Penn State

Liu clarified that these small polar regions are not fixed. Rather, they are in a constant state of fluctuation and are dynamic, enabling them to react at optical speeds.

“This behavior is very different from typical ferroelectrics,” said Yan.

Liu's zentropy theory provided the team with insights into the reasons behind the distinct behavior of the new ceramics, which deviated significantly from the predictions made by existing ferroelectric models.

According to Liu, zentropy is intended to encapsulate the continuous shifting, vibrating, and rearranging of atoms within a material. This is a phenomenon that conventional theories often dismiss as mere background noise.

The researchers were able to chart all the minute structural states that the atoms could assume and subsequently compute how these rapid fluctuations collectively impact the overall performance of the material using the concept of zentropy.

This methodology proves particularly advantageous for ferroelectrics, whose internal structures exhibit high levels of dynamism, especially at the elevated frequencies employed in photonics, as stated by the researchers.

The researchers discovered that zentropy theory could elucidate why the small, rapidly moving polar regions they identified were capable of responding at optical speeds. When a material's internal structure disintegrates into these minuscule, fluctuating units, the energy required for polarization reversal becomes exceedingly low.

The material can adapt to an applied electric field almost instantaneously, resulting in the ultrahigh electro-optic response observed in the experiments. Traditional theories, which posit larger and slower-moving domain structures, were unable to explain this behavior.

Liu emphasized that zentropy demonstrated that the exceptional performance was not merely a fortunate coincidence but rather a natural outcome of the atomic-scale dynamics of the

material.

“ *By breaking the larger system into smaller atomic units, the energy barrier for polarization changes becomes much lower. That allows the response to be extremely fast.*

Zi-Kui Liu, Professor, Materials Science and Engineering, Penn State

This comprehension is essential for the future scalability of transparent ceramics production, Liu stated. The researchers have already shown that their ceramics can be consistently produced at a laboratory scale, and they are currently focused on increasing production, assessing long-term reliability, and creating safer lead-free alternatives for the industry.

“ *With progress in these areas, we are optimistic that practical devices could follow in the near future.*

Zi-Kui Liu, Professor, Materials Science and Engineering, Penn State

These innovative devices have the potential to transform essential optical technologies, including fiber optic internet systems, autonomous vehicle navigation, and advanced medical diagnostics, among others, which drive the contemporary digital economy, according to the researchers.

The team noted that lithium niobate has served as the primary material in these applications for many years. The application of electricity alters the way lithium niobate refracts light, but the change is minimal, akin to shifting a ruler by the thickness of a few atoms. The ceramics introduced in this recent study exhibit coefficients that significantly exceed that degree.

“ These materials could pave the way for a new generation of electro-optic devices that are smaller, faster, more energy efficient, and lower cost. Potential applications include optical modulators, optical switches, communication components, sensors, and integrated photonics.

Haixue Yan, Materials Science and Engineering Student, Queen Mary University of London

Journal Reference:

Jiang, Q., et al. (2025) Dynamic Atomistic Polar Structure Underpins Ultrahigh Linear Electro-Optic Coefficient in Transparent Ferroelectric Ceramics. *Journal of the American Chemical Society*. DOI: 10.1021/jacs.5c15699.

Sources:

- The Pennsylvania State University
- <https://pubs.acs.org/doi/10.1021/jacs.5c15699>

Ceramics: Oxides vs Nitrides

Far more than a material for crockery and tableware, ceramics are getting an upgrade in engineering. From electric fields to AI, researchers are transforming these traditional composites.



Image Credit: AU USAnakul/Shutterstock.com

What are Ceramics?

Ceramics are a class of inorganic, non-metallic materials held together through ionic and covalent bonding.

Their atomic structure is defined by a rigid lattice network formed during high-temperature processing routes, such as sintering. This crystallographic structure yields high melting points, high hardness, chemical inertness, and electrical insulation properties.

Strong ionic and covalent bonds resist plastic deformation and prevent dislocation motion, which limits plastic strain capability to less than 0.1 % at RTP.

This restriction results in brittle fracture under tensile or cyclic loading, but does not

compromise their ability to sustain compressive strengths exceeding 1000 MPa or maintain structural stability at temperatures where metallic systems melt or oxidize.

With such strength, stability, and resistance to deformation, ceramics are well-positioned as functional materials for aerospace structures, electronic substrates, protective armor, energy conversion components, and more.¹

Ceramics have been used since at least 28,000 BCE, beginning with fired clay figurines and later evolving into pottery and functional containers.

Technological advances, from the potter's wheel to expanded trade networks, and industrial innovations from the 15th century onward have enabled the development of refractory and technical ceramics.

Over time, ceramics have evolved from simple functional objects to engineered materials with properties optimized for a wide range of modern industrial uses.²

Types of Ceramics Used in Industry

Oxide Ceramics

Oxide ceramics comprise inorganic and non-metallic compounds based on metal oxides such as aluminum, zirconium, silicon, and magnesium.

Their structure is dominated by oxygen anions bonded to metallic cations, resulting in high thermal stability, chemical inertness, and a wide range of electrical characteristics.

These can vary from insulating to semiconducting grades, depending on composition and microstructure.

Alumina (Al_2O_3) is the most widely used oxide ceramic. It has high hardness, electrical insulation, and stability up to approximately 1500 °C, with dense grades achieving Vickers hardness values of around 20 GPa.

These properties make alumina highly valuable for substrates, seals, crucibles, and structural components in electronics, chemical processing, and high-temperature engineering applications, where metallic components would otherwise oxidize, distort, or melt.



Applying ceramic coatings to the body of a car can protect against damage. Image Credit: Vershinin89/Shutterstock.com

Non-Oxide Ceramics

Non-oxide ceramics include compounds such as carbides, nitrides, and borides. These materials exhibit covalent bonding that produces greater hardness and refractory characteristics than oxide ceramics. The absence of oxygen results in improved thermal conductivity and mechanical properties at elevated temperatures, though many non-oxide ceramics demonstrate susceptibility to oxidation.

Silicon carbide (SiC) is one of the hardest ceramic materials, with a Mohs hardness of approximately 9.5, a thermal conductivity of approximately 120 W/m K, and flexural strengths exceeding 400 MPa at elevated temperatures.

These properties support abrasive grinding wheels, heat exchanger components, semiconductor substrates for high-voltage and high-frequency power electronics, and advanced armor systems where high hardness and low density reduce areal mass.

The automotive industry is increasingly adopting silicon carbide in brake discs and diesel particulate filters.

Silicate Ceramics

Silicate ceramics comprise traditional clay-based materials alongside modern engineered compositions. They contain silicon-oxygen tetrahedra as their fundamental structural units, often combined with elements such as aluminum, magnesium, and calcium.

The silicate framework offers broad compositional flexibility and supports various processing routes, ranging from low-cost clay formation to engineered sintering for enhanced performance.

Although silicate ceramics generally do not match the extreme hardness, refractoriness, or thermal conductivity of oxide or non-oxide ceramics, they are cost-effective and reliable for structural and thermal applications that do not demand ultra-high performance metrics.

Porcelain is one of the most common silicate ceramics. It is composed primarily of kaolin, feldspar, and quartz.

Porcelain's characteristic properties result from vitrification during firing, where feldspar melts to form a glassy matrix that binds quartz particles and mullite crystals.

Its microstructure provides excellent electrical insulation with breakdown strengths exceeding 10 kV per mm, alongside high chemical resistance and low water absorption.

Technical grades of porcelain achieve flexural strengths in the range of 100 to 150 MPa. As a result, they can be used in high-voltage insulators, laboratory crucibles, sanitary ware, and architectural components where electrical reliability, impermeability, and dimensional stability are required.

Glass Ceramics

Glass-ceramics are a hybrid class initially formed as amorphous glass through conventional melting processes, then subjected to controlled crystallization heat treatments. This dual-stage processing combines the formability of glass with enhanced properties approaching those of polycrystalline ceramics.

The resulting microstructure consists of fine-grained crystalline phases, typically comprising 50-95 % of the volume, dispersed within a residual glass matrix.

Lithium aluminosilicate-based glass ceramics represent a specialized family within this category because controlled crystallization produces β -spodumene or β -quartz solid solution

phases that achieve near-zero thermal expansion coefficients below $1 \times 10^{-6}/^{\circ}\text{C}$.

This yields exceptional thermal shock resistance and dimensional stability under severe thermal gradients. These materials are therefore employed in cooktop panels, telescope mirror substrates, and cookware where thermal stability must be maintained while sustaining mechanical strengths between 100 and 200 MPa at continuous operating temperatures approaching 700 °C.^{1,3,4}

Comparative Analysis of Ceramic Types

Ceramic Type	Key Advantages	Primary Disadvantages	Typical Cost	Maximum Temperature
Oxide	Oxidation resistance; electrical insulation; chemical inertness	Limited fracture toughness	Low-Moderate	1600-1800 °C
Non-Oxide	Superior hardness; high thermal conductivity	Oxidation susceptibility; challenging machining	Moderate-High	1400-2000 °C
Silicate	Low production costs; processing flexibility	Lower strength versus advanced ceramics	Low	1000-1400 °C
Glass-Ceramic	Complex shape formation; thermal shock resistance	Limited maximum temperatures	Moderate	700-1200 °C

Table 1: A comparative analysis of different ceramic types - advantages, disadvantages, typical cost, and temperature.

Recent Advances in Ceramic Processing

AI-Optimized Processing for High-Temperature Structural Ceramics

A [DARPA](#)-funded research effort enhanced the toughness and thermal stability of aluminum-doped boron carbide through hot forging and reaction sintering, supported by physics-based machine learning optimization.

The work integrated experimental characterization, atomic-scale simulation, and predictive models to link processing parameters to defect formation and toughening mechanisms.

The researchers aimed to achieve an order-of-magnitude increase in toughness while maintaining high strength to address the brittleness limitation that currently restricts ceramic deployment in high-temperature structural environments.

This approach offers a pathway to produce structurally reliable ceramics for aerospace, defense, and other sectors that require lightweight, high-temperature systems.⁵

3D Printing Technical Ceramics

Here, [Steinbach AG Technical Ceramics](#) demonstrates how [additive manufacturing](#) can further transform the industry:



Video Credit: Steinbach AG/YouTube.com

Surface Layer Removal for Enhanced Wear Resistance

A study published in [Ceramics](#) demonstrated that the surface integrity and wear performance of ZrO_2 , Al_2O_3 , and Si_3N_4 ceramics can be improved by removing the defective layer formed during diamond grinding.

The researchers used a fast neutral argon atom beam system to selectively remove the defective layer, which contained deep grooves, microcracks, grain pull-out, and tensile stress fields that acted as failure initiation sites under mechanical loading.

The removal of surface damage reduced abrasive wear by an order of magnitude and improved adhesion of subsequently deposited functional coatings.

This process enhances the mechanical reliability and extends the service life of ceramics in demanding applications such as cutting tools, wear-resistant components, and high-performance structural parts.⁶

Electric Field-Assisted Sintering for Enhanced Ductility

A study published in the [Science Advances](#) presents a reinforcement strategy to enhance the ductility and fracture resistance of ceramics by applying an electric field during sintering, a process known as flash sintering.

The technique generates a high density of nanoscale defects, including stacking faults, nanotwins, and dislocations within titanium dioxide, allowing plastic deformation at room temperature before catastrophic failure.

This defect-induced mechanism eliminates the high nucleation stress typically required for brittle fracture, effectively transforming a conventionally brittle material into one capable of sustaining compression strains comparable to those of metals.

This approach is significant because improved low-temperature ductility expands the operational envelope of ceramics used in aerospace, defense, automotive, nuclear, and sustainable energy hardware, enabling higher reliability under load without resorting to extremely high-temperature operation or complex composite architectures.⁷

Conclusion

Ceramics are highly valued for their high hardness, thermal stability, and chemical resistance. However, their intrinsic brittleness and limited tensile strength remain significant challenges for broader structural applications.

Ongoing research focused on microstructure control, composite reinforcement, and advanced processing techniques aims to enhance toughness, reliability, and multifunctionality, expanding the applicability of ceramics across demanding industrial domains.

References and Further Reading

1. Giordano II, R. (2022). Ceramics overview. *British Dental Journal*, 232(9), 658-663.

<https://doi.org/10.1038/s41415-022-4242-6>

2. ACerS. (2025). A Brief History of Ceramics and Glass. <https://ceramics.org/about/what-are-ceramics/a-brief-history-of-ceramics-and-glass/>
3. Advanced Ceramic Materials. (2025). Types and Applications of All Kinds of Ceramic Materials. <https://www.preciseceramic.com/blog/types-and-applications-of-all-kinds-of-ceramic-materials.html>
4. Roux, V. (2019). Ceramics and Society. SpringerLink. <https://doi.org/10.1007-978-3-030-03973-8>
5. McKenna, D. (2025). Dimitris Giovanis and Somdatta Goswami Receive DARPA INTACT Grant to Develop Heat-Resistant Ceramics. <https://engineering.jhu.edu/case/news/dimitris-giovanis-and-somdatta-goswami-receive-darpa-intact-grant-to-develop-heat-resistant-ceramics/>
6. Metel, A. S., Volosova, M. A., Mustafaev, E. S., Melnik, Y. A., Okunkova, A. A., & Grigoriev, S. N. (2024). Improving the Quality of Ceramic Products by Removing the Defective Surface Layer. *Ceramics*, 7(1), 55-67. <https://doi.org/10.3390/ceramics7010005>
7. Li, J., Cho, J., Ding, J., Charalambous, H., Xue, S., Wang, H., Phuah, X. L., Jian, J., Wang, X., Ophus, C., Tsakalakos, T., García, R. E., Mukherjee, A. K., Bernstein, N., Hellberg, C. S., Wang, H., & Zhang, X. (2019). Nanoscale stacking fault-assisted room temperature plasticity in flash-sintered TiO₂. *Science Advances*. <https://doi.org/aaw5519>

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Metallographic preparation of technical ceramics

Metallographic preparation of technical ceramics is a critical process to reveal microstructural features such as grain size, porosity, and phase distribution. Due to their high hardness and brittleness, ceramics require precise and controlled preparation steps.

The process typically begins with sectioning using precision cutting machines like QATM's Qcut 200 A, ensuring minimal damage.

This is followed by **mounting**, often with cold mounting processes, to provide stability during grinding and polishing.

Grinding is performed using diamond grinding discs, as conventional abrasives are insufficient for ceramics. The VEGA diamond discs with metal bonding are the most appropriate medium to grind ceramic samples. **Polishing** is then carried out in multiple stages with diamond suspensions of decreasing grain size, often on table polishing machines like Qpol 250 A1 or Qpol 300 A1 Eco+ polishing machines, to achieve a scratch- and deformation-free surface. **Final polishing** may involve oxide suspensions for enhanced surface quality.

Proper cleaning between steps and optimized parameter control are essential to avoid artifacts and **ensure reproducible, high-quality results**.

Download the
Application Note

Get in touch with
our experts

Engineering Technical Ceramics Through Particle Insight

Performance in technical ceramics is not specified at the end of processing; rather, it is engineered gradually, beginning at the particle level. The behavior of ceramic materials, whether in dry powders, concentrated slurries, or sophisticated suspensions, is essentially determined by particle size, shape, and interactions.

These parameters influence packing efficiency, flow behavior, dispersion quality, and stability, eventually determining the microstructure and functional qualities of the finished component.

Modern characterization techniques allow for the understanding and manipulation of these features with unparalleled precision.

Manufacturers can use dynamic image analysis, laser diffraction, dynamic light scattering, Zeta potential, and stability analysis to develop formulations more predictably and effectively than trial-and-error experiments.

This integrated method allows for quicker development cycles, better reproducibility, and more reliable ceramic products.

1. Engineering Performance at the Powder Stage

Ceramic extrudates play an important role in heterogeneous catalysis, especially in petrochemical processing, refinery operations, and environmental applications. These materials are typically generated as rod-shaped particles, often known as pellets, and are filled into reactors.

The extrudates' geometric qualities are critical: their length, diameter, aspect ratio, and general uniformity have a direct impact on packing density, pressure drop, mechanical stability, and gas and liquid flow behavior through the catalyst bed.

Even minor differences in particle size or shape uniformity might result in channeling, irregular residence durations, or premature mechanical degradation, which can reduce reactor performance and catalytic efficiency. Extrusion is used to make many different ceramic components, and they are held to identical quality standards.

CAMSIZER 3D



The CAMSIZER 3D Particle Size & Shape Analyzer from MICROTRAC. Image Credit: Microtrac

CAMSIZER 3D and its proprietary dynamic image analysis (DIA) technology offer a realistic approach for characterizing these particles.

Instead of using a single random projection per particle, as in typical two-dimensional DIA, each particle is monitored as it moves across the camera's field of vision. Particles are thus recorded in multiple orientations as they freely fall, facilitating precise measurement of their true dimensions.

As a result, the system can determine the actual maximum length, width, and thickness, meaning that particle geometry is captured in a manner that closely approximates genuine physical dimensions.

This difference becomes very clear when comparing measurement methods. While traditional 2D image analysis tends to underestimate particle length due to orientation effects, 3D tracking produces excellent agreement with physical caliper measurements.

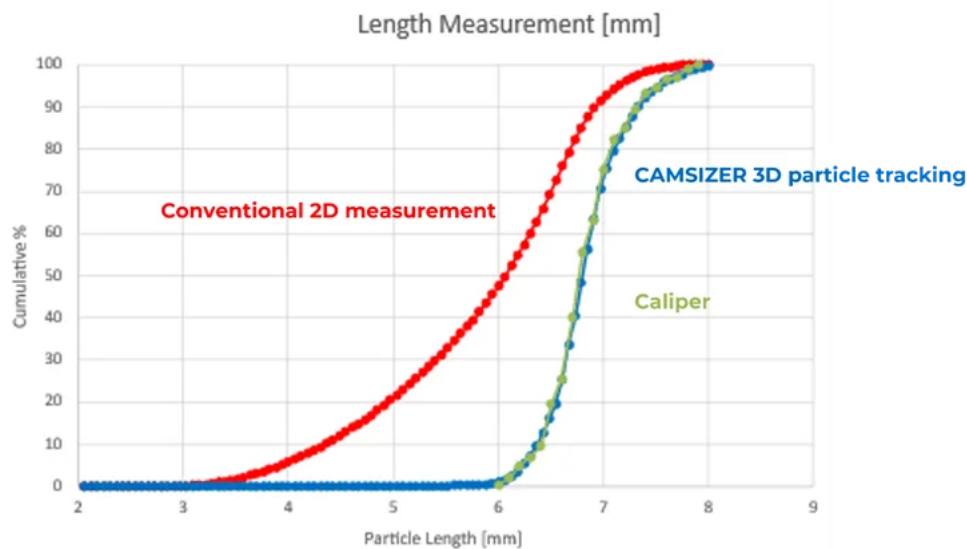


Figure 1. Particle length distribution of a ceramic extrudate sample. Image Credit: Microtrac

The impact extends beyond size into shape characterization. Two-dimensional approaches underestimate length, meaning they skew the aspect ratio, making particles appear less elongated than they actually are.

In contrast, 3D analysis generates consistent and relevant form descriptors, which are critical for understanding process behavior.

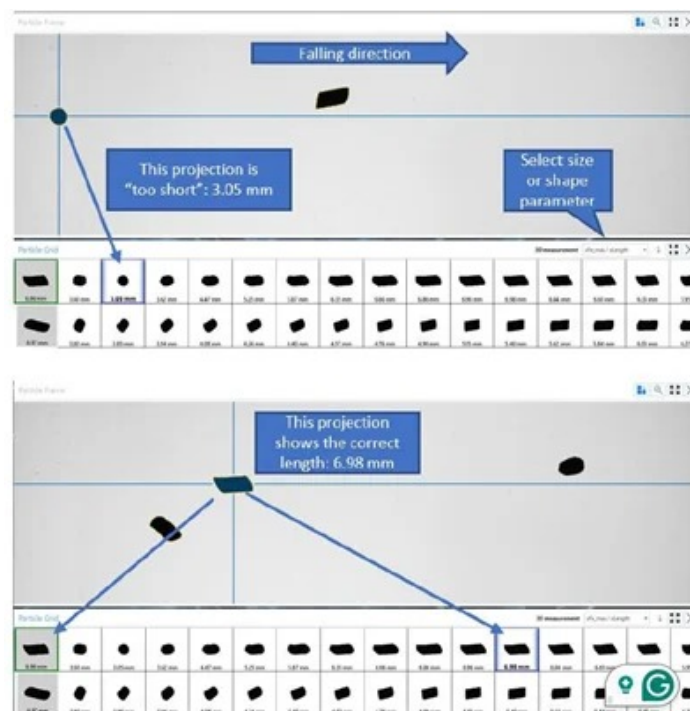


Figure 2. Analysis of particle tracks – the individual projections of one particle are listed from left to right. Image Credit: Microtrac

However, when dealing with powder systems, size distribution must be examined over a wide range. Ceramic materials frequently contain small particles in the micron or submicron range, as well as coarse particles larger than one millimeter in size.

This is evident in the example below, which compares materials like alumina, bauxite, and silicon carbide. While alumina particles have limited distributions of a few microns, bauxite and SiC have large distributions that extend into the millimeter range.

Laser diffraction delivers accurate and reproducible measurements of small particles, but for coarse and irregular materials, image analysis is a helpful supplement. The SYNC method combines both techniques, capturing fine and coarse fractions concurrently and delivering a comprehensive view of the material.

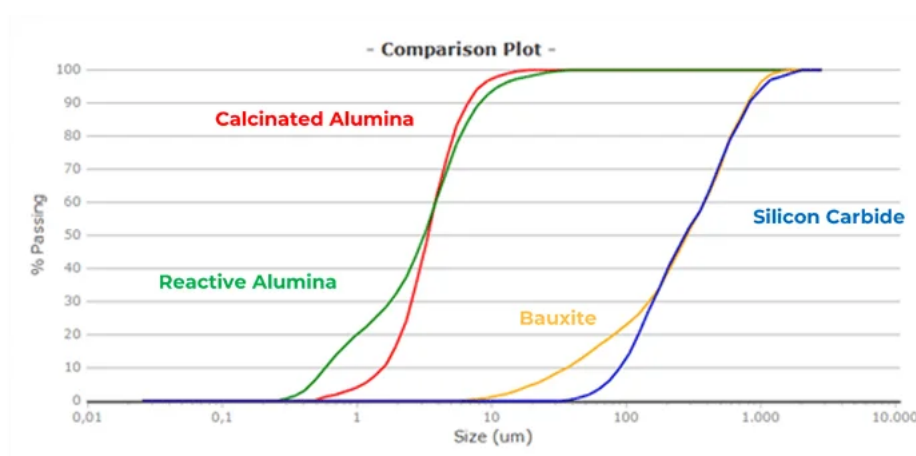


Figure 3. Comparison of the volume-based distributions (Q3) of four samples. Image Credit: Microtrac

Table 1. Percentiles (d10/d50/d90/d95). Source: Microtrac

Id1:	Calcinated Alumina	Reactive Alumina	Bauxite	Silicon Carbide
10 %tile [µm]	1.56	0.575	35.47	89.61
50 %tile [µm]	3.35	3.15	281.9	272.7
90 %tile [µm]	6.59	8.11	796.6	819.6
95 %tile [µm]	8.19	11.26	935.0	1038

Laser Diffraction analysis often has trouble recognizing large particles in a sample, so it is often combined with image analysis when dealing with broad particle size distributions. The example shows large particles in the bauxite and SiC samples, which augment and verify the laser diffraction measurement.

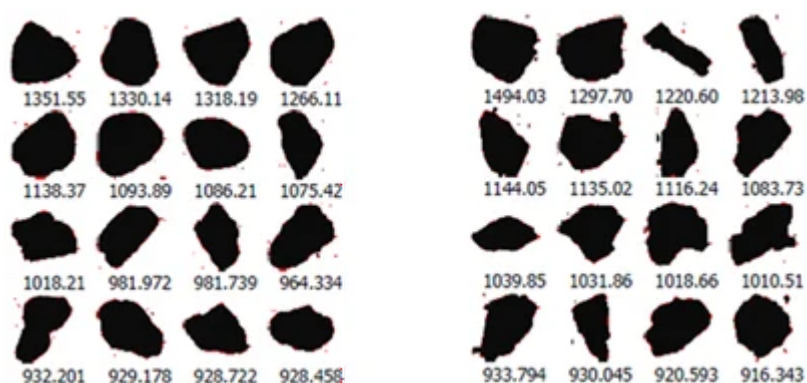


Figure 4. Oversized particles captured by the camera of the SYNC analyzer. Bauxite (left) and SiC (right). Particle size is below the images. Note that the largest particles are almost 1.5 mm. Image Credit: Microtrac

2. Porosity and Surface Area Characterization of Ceramic Extrudates for Catalytic Applications

The aforementioned ceramic extrudates play an important role in heterogeneous catalysis, especially in petrochemical processing, refinery operations, and environmental applications.

As well as their geometric qualities, critical design parameters such as surface area, porosity, surface chemistry, and cyclic stability must be carefully analyzed and verified.

Among these factors, porosity is extremely important in ceramic materials and must be carefully managed. Increasing porosity improves mass transfer and functional performance but reduces mechanical strength and structural robustness.

Low-porosity ceramics have a dense structure with minimal vacancies. This results in high mechanical strength and chemical durability, making them ideal for demanding situations such as catalyst supports under high pressure.

Their limited number of open channels, however, results in poor permeability and low thermal insulation. As a result, gas diffusion is restricted and heat is transferred rather than retained, reducing their effectiveness in applications that require mass transfer.

Contrastingly, high-porosity ceramics have a network of interconnected pores that promote gas transport and permeability. This is especially useful in catalytic extrudates, where reactants must efficiently reach active sites.

Increasing porosity, however, diminishes mechanical strength, making materials more prone

to breaking during handling and operation. In addition, increased exposed surface area can marginally lessen chemical resistance.

To fully characterize surface area and porosity, a variety of analytical approaches are necessary. Common methods include gas adsorption and mercury intrusion porosimetry.

Each technique focuses on a certain pore size range and gives complementing data, adding to a comprehensive understanding of the surface area and pore structure.



A selection of MICROTRAC gas adsorption analyzers: BELSORP MAX G, BELSORP MAX X, BELSORP MINI X, BELSORP MR1. Image Credit: Microtrac



MICROTRAC's BELPORE mercury porosimeter series for low-pressure (LP), medium-pressure (MP), and high-pressure (HP) reliably and reproducibly measures pore diameters from 1 mm to 3.6 nm. Image Credit: Microtrac

Gas adsorption analysis offers extensive information on specific surface area, pore volume, and pore size distribution from 0.35–500 nm.

These characteristics have a significant impact on the reactivity, sintering behavior, and overall functional performance of ceramics, particularly in catalysts, sensors, and filtration systems.

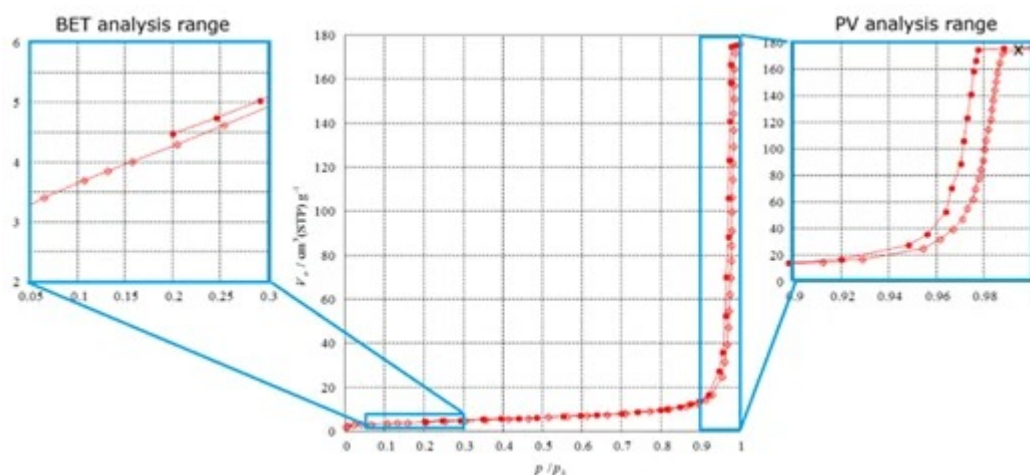


Figure 5. Nitrogen sorption isotherm of an alumina-based ceramic sample at 77 K, with annotations indicating the relevant evaluation ranges of the adsorption process. The BET region (relative pressure $p/p_0 = 0.05$ – 0.30) is enlarged on the left, while the pore volume analysis range is enlarged on the right. The pore size distribution is derived from the full analysis range. Image

Credit: Microtrac

The Brunauer-Emmett-Teller (BET) method (ISO 9277) is the most commonly used approach for calculating specific surface area (SSA). It measures the quantity of physisorbed gas in both nonporous and micro- to macroporous substances.

The calculation uses the linearized BET plot to compute the monolayer capacity and the adsorbate molecule's cross-sectional area (0.162 nm^2 for nitrogen). Using these factors, the SSA (m^2/g) may be determined.

Pore volume (PV) can also be assessed. While PSD methods frequently provide information on associated pore volumes, the overall pore volume is typically calculated using Gurvich's approach.

This method translates the adsorbed amount at high relative pressure (usually $p/p_0 = 0.99$), where the pores are believed to be filled by condensed adsorbate, into the total pore volume.

Finally, the pore size distribution (PSD) is an important part of material characterization. Micropores and mesopores have diverse adsorption properties, so they are often studied independently using various methodologies and models.

Traditionally, PSDs have been derived using both empirical and theoretical methodologies. Methods such as BJH, DH, CI, and INNES can be employed for mesoporous materials, each with their own set of assumptions, such as pore geometry.

Source: Microtrac

Results by the BJH method (Harkins-Jura t-plot)	Results by MIP (SA model Cylindrical and Plate)
BET-SA 15.282 [m ² g ⁻¹]	ap 15.597 [m ² g ⁻¹]
Pore volume (p/p ₀ =0.9900) 0.2671 [cm ³ g ⁻¹]	Pore volume 0.2711 [cm ³ g ⁻¹]
	Average pore diameter 69.53 [nm]

Ceramic materials are often meso- to macroporous and frequently have hierarchical pore patterns, making mercury intrusion porosimetry (MIP) an essential characterization technique.

This method, detailed in ISO 15901-1, is based on driving non-wetting mercury into the pore system at an ambient temperature, by applying pressures of up to 414 MPa. The pore width ranges from roughly 1000 μm to 3.6 nm. The Washburn equation states that the pore diameter is inversely proportional to the applied pressure ($d = (4\gamma \cos \theta) / p$).

The volume of intruded mercury, as determined simultaneously by capacitance measurement, is proportional to the material's accessible pore volume.

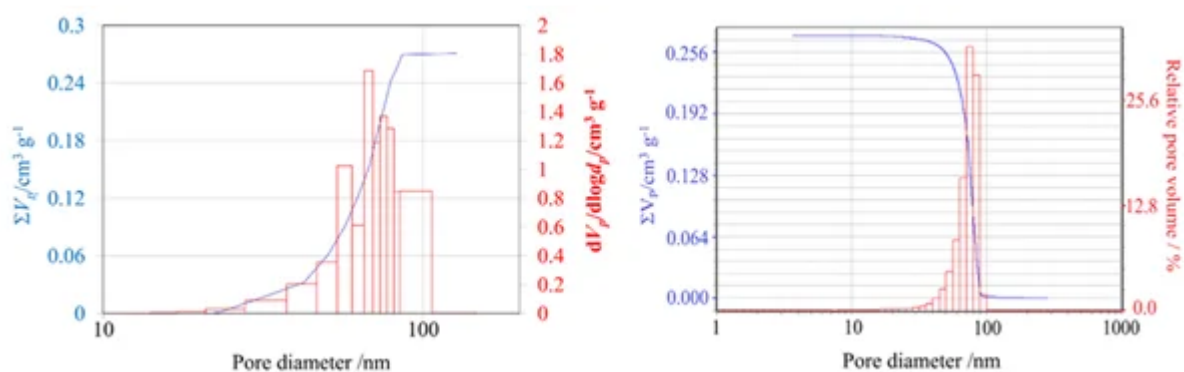


Figure 6. Pore size distribution calculation based on gas adsorption analysis (left) and mercury intrusion porosimetry (right). Image Credit: Microtrac

Table 2. Comparison of pore size distribution and porosity analysis by gas adsorption and mercury intrusion porosimetry. Source: Microtrac

Results by BJH method (Harkins-Jura t-plot)	Results by MIP (SA model Cylindrical and Plate)
Pore volume 0.2711 [cm ³ g ⁻¹]	Intra pore volume 0.2738 [cm ³ /g]
Surface Area 15.597 [m ² g ⁻¹]	Intra-pore surface area 16.106 [m ² /g]
Average pore diameter 69.53 [nm]	Average pore diameter 68.0 [nm]

Gas adsorption and mercury intrusion porosimetry (MIP) are only applicable within a specific pore size range. MIP is insufficient for the precise characterization of micropores due to accessibility and pressure constraints, while gas adsorption techniques become less reliable for bigger macropores.

The close agreement seen here suggests that the pore structure falls within the overlapping measurement ranges of both approaches.

The surface area and porosity of ceramic materials are extremely sensitive to synthesis, shape, and thermal treatment conditions, so accurate characterization is critical.

Characteristics such as raw materials, particle size, additives, and processing methods all have an impact on pore structure, connectivity, and, ultimately, material performance, with tiny alterations causing major differences.

Advanced analytical techniques, including gas adsorption and MIP, are critical for measuring these properties across the relevant pore size ranges. They offer a greater knowledge of process-structure connections by providing detailed information on surface area, pore volume, and pore size distribution, as well as focused optimization of ceramic materials for specific applications.

3. From Powders to Slurries: Controlling Dispersion

As powders turn into slurries, the emphasis switches from geometry to interaction. The way that particles behave in a liquid environment - whether they remain scattered or form aggregates - becomes equally as important as the particles' shapes.

NANOTRAC FLEX, which employs Dynamic Light Scattering (DLS), provides insight into nanoscale behavior. For example, during silica particle formation, DLS can measure particle

growth in real time, displaying size evolution from roughly 178 nm to nearly 400 nm. These measurements closely match TEM data, indicating precision and the capacity to monitor operations as they occur.



MICROTRAC’s NANOTRAC FLEX Nanoparticle Size Analyzer and STABINO ZETA Zeta Potential Analyzer. Image Credit: Microtrac

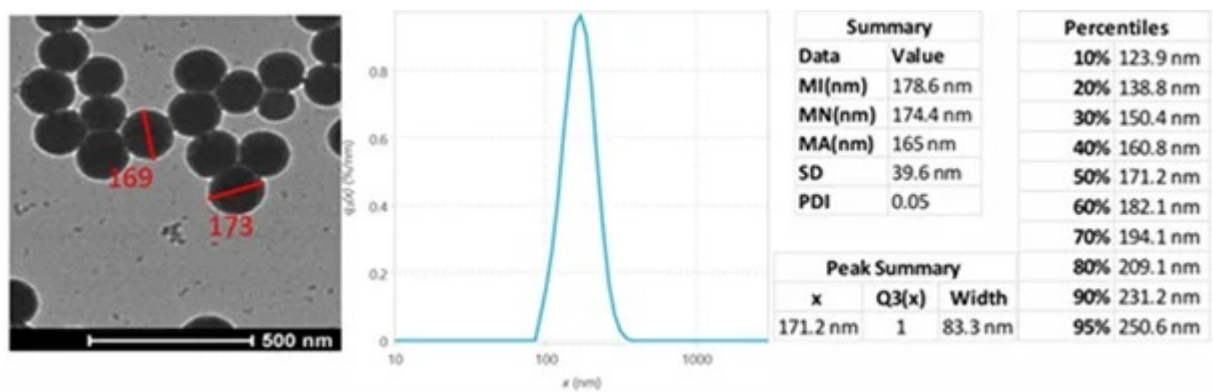


Figure 7. Precise measurements of various sizes of silica nanoparticles, validating the accuracy of Microtrac Flex dynamic light scattering (DLS) by comparison with Transmission Electron Microscope (TEM) data. In the DLS method, samples were measured conventionally by immersing the probe in the sample. Image Credit: Microtrac

This technique has the advantage of being able to measure a wide range of concentrations, from highly diluted solutions to industrially relevant suspensions. This reduces the need for unnecessary dilution, allowing measurements to reflect actual processing conditions.

While particle size is useful information, it does not entirely explain stability: particle charge has an equally essential role.

Zeta Potential measurements show how particles interact, revealing stable regions and predicting aggregation behavior. In alumina dispersions, for example, coagulation begins before the isoelectric point is achieved, demonstrating that instability can arise long before complete charge neutralization.

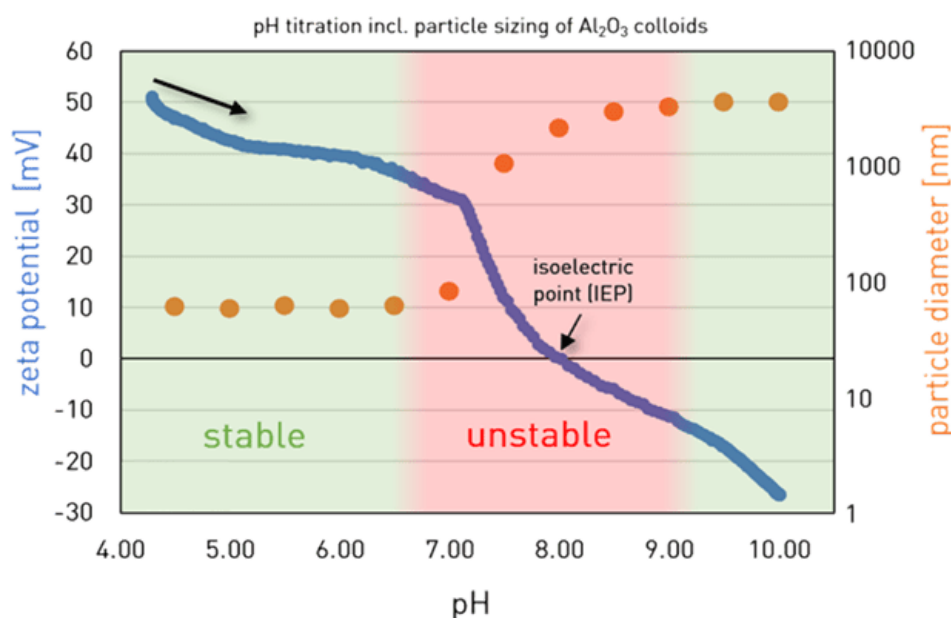


Figure 8. Blue curve: Fast particle charge titration of an alumina dispersion with NaOH. Orange curve: Simultaneous size [nm] measurements. Image Credit: Microtrac

Combining size and charge measurements allows users to detect the onset of aggregation and improve formulations accordingly. Polyelectrolyte titrations improve this capability by determining the crucial point at which dispersion begins to break down.

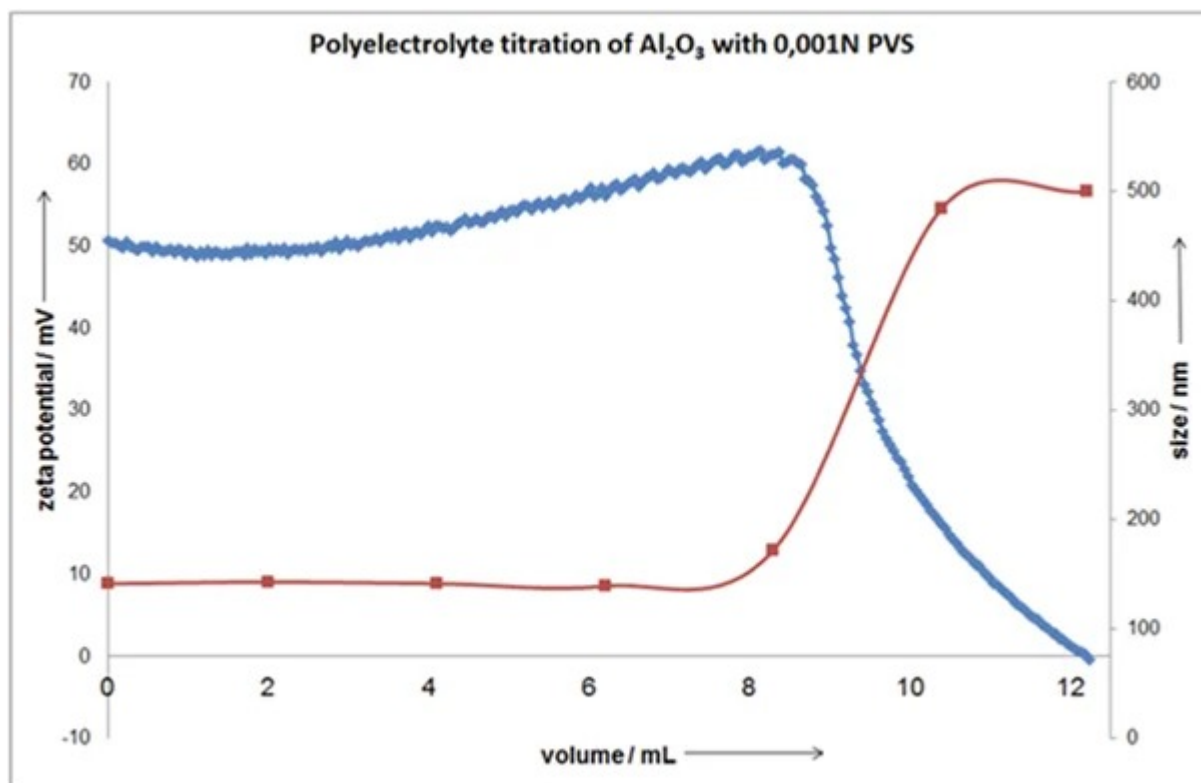


Figure 9. Polyelectrolyte titration with simultaneous size measurement. Image Credit: Microtrac

This combination method turns slurry formulation into a controlled, data-driven process, allowing for faster optimization and improved consistency.

4. From Stability to Usability: Sedimentation and Redispersion

Even a well-dispersed slurry and strong particle-particle repulsion are not necessarily stable. Most ceramic suspensions will undergo sedimentation with time, resulting in phase separation and performance changes. However, stability is not the only factor that determines usability: a formulation must also be redispersible.

TURBISCAN technology allows for early detection of instability by scanning the sample's height and tracking variations in backscattering over time. This method detects sediment production at the bottom and clarification at the top, before these changes become noticeable.



MICROTRAC's TURBISCAN range for Stability, Shelf-Life, and Dispersibility Analysis. Image Credit: Microtrac

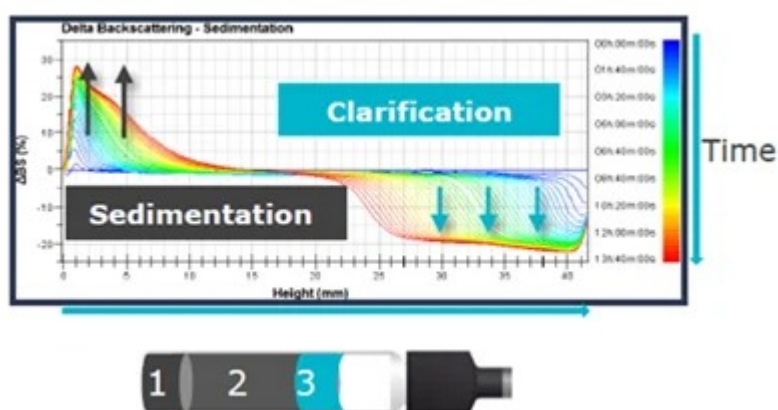


Figure 10. Sedimentation graph with TURBISCAN. Image Credit: Microtrac

To facilitate easy comparison between formulations, the Turbiscan Stability Index (TSI) gives a single numeric value that reflects overall destabilization. This enables the rapid ranking of samples, frequently within hours.

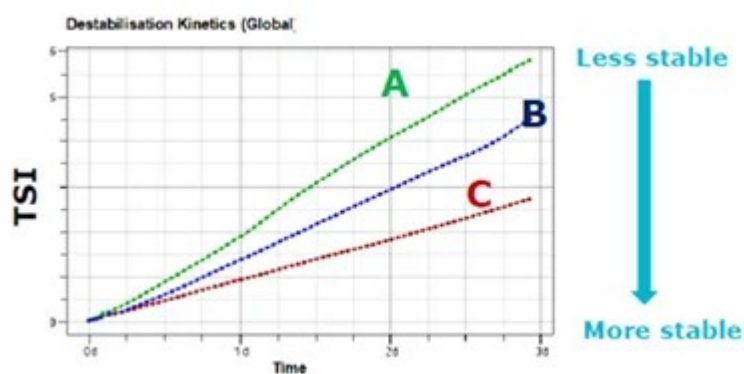


Figure 11. TSI kinetics over three days. Image Credit: Microtrac

Beyond ranking, the approach provides precise information about sediment structure and

kinetics. Sediment thickness, compactness, and settling velocity are all factors that contribute to a system's instability.

Following this, the most important practical question is whether the system can be restored. Redispersibility studies determine how well a formulation recovers to its original state under controlled mixing.

The completeness and speed of redispersion can be assessed by comparing the recovered backscattering signal to the initial state.

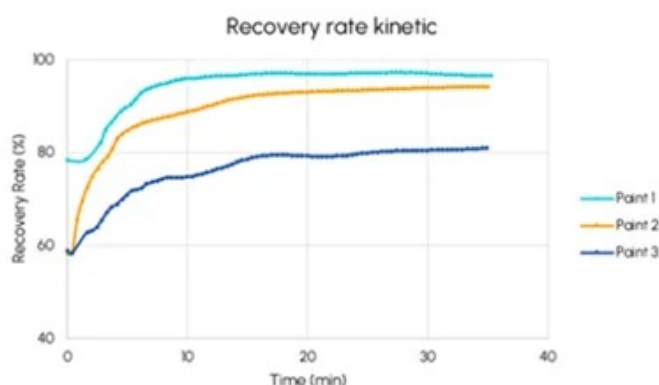


Figure 12. Recovery rate (%) as a function of time (minutes) for three points. Image Credit: Microtrac

This is especially relevant in ceramic inks: clear differences can be seen when comparing three formulations with similar pigments but different solutions. One formulation has low sedimentation and good redispersibility, whereas another settles quickly and cannot be completely restored. Viscosity is important here, as more viscosity slows sedimentation but does not guarantee redispersibility.

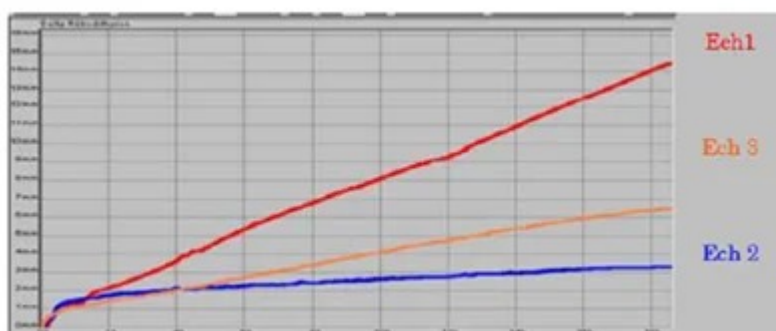


Figure 13: Comparison of sedimentation kinetics between three samples. Image Credit: Microtrac

Conclusion

Particle behavior ultimately governs performance throughout the ceramic production chain, from powders to suspensions. Combining complementary characterization techniques allows users to connect size, shape, interaction, and stability into a single cohesive understanding.

Rather than depending on measurements in isolation, this integrated approach establishes a continuous link between raw materials, processing conditions, and ultimate product performance.

It enables manufacturers to detect issues earlier, optimize formulations more efficiently, and ensure consistent quality in increasingly complex ceramic systems.

In this way, particle characterization transitions from a supporting analytical step to a primary instrument for innovation, facilitating measurement and, importantly, genuine control over material behavior.



This information has been sourced, reviewed, and adapted from materials provided by Microtrac.

For more information on this source, please visit [Microtrac](#).

Radiation-Resistant Materials: Tough Space Materials

Without the comfort of an ozone cushion, space is punishing on materials. High-energy ionizing radiation, ultraviolet light, atomic oxygen, extreme thermal cycling, and micrometeoroids create an erratic atmosphere; Earth-stable materials are rapidly broken down in these conditions.



Image Credit: Artsiom P/Shutterstock.com

Radiation-resistant, tough space materials are therefore a necessity for missions that go beyond our safe atmosphere.

Modern spacecraft, space stations, and deep-space probes use such materials engineered to maintain dimensional stability, mechanical strength, and functional performance over long durations. These materials are selected or designed to balance low mass, predictable degradation, and manufacturability. They must also meet specific mission needs for protection, support, and electronics safety.

In space, radiation comes from trapped particles in planetary belts, solar energetic particles during solar events, and galactic cosmic rays that span a wide range of energies and atomic numbers. These particles can knock atoms out of place in a material's lattice, carve ionized

tracks, and generate secondary radiation that further stresses polymers, [ceramics](#), and metals.

Over time, cumulative radiation exposure can embrittle metals, darken optical coatings, and cause gas release or cracking in polymers, all of which reduce structural integrity and reliability.^{1,2}

Non-ionizing UV radiation and atomic oxygen in low Earth orbit further challenge organic materials and coatings, removing surface layers and altering thermal and electrical properties. Thermal cycling between extreme high and low temperatures can cause cracking at interfaces, while micrometeoroid impacts and debris can initiate localized damage that grows under repeated mechanical and radiation stress.

Radiation-resistant materials are designed to handle these hazards with stable microstructures, low-outgassing chemistries, and built-in shielding against particle and photon radiation.^{2,3,4}

Advanced Polymers for Lightweight Shielding and Structures

Polymer-based materials are important for radiation-resistant space systems due to their low density, high hydrogen content, and tunable mechanical and electrical properties.

Common options, like polyethylene, polyimide, polyether ether ketone (PEEK), and polydimethylsiloxane (PDMS), are used in structural substrates, thermal blankets, and radiation shields.

These materials can be loaded with nanoparticles or fillers, such as boron carbide or bismuth oxide, to strengthen their protection against neutrons, protons, and gamma rays.^{1,3,4}

Recent work in [Composites Science and Technology](#) reports that hydrogen-rich benzoxazine resins reinforced with amine-functionalized multi-walled carbon nanotubes can deliver higher tensile strength and improved resistance to atomic oxygen and outgassing compared with standard epoxy-based shields.

This combination of properties makes it possible to form thin, lightweight panels to guard onboard electronics from cosmic radiation. [Silicone-based systems](#) remain a practical choice for flexible membranes and seals, where repeated flexing and thermal cycling can't be allowed to compromise performance.^{4,5}

Ceramic Matrix Composites for Extreme Environments



Image Credit: Artsiom P/Shutterstock.com

Ceramic matrix composites (CMCs) are used when temperature stability, low density, and chemical inertness are as important as radiation resistance. In CMCs, ceramic fibers (often silicon carbide or alumina) are embedded in a ceramic matrix, creating a material that can tolerate long-term exposure to atomic oxygen, plasma, and high-energy ions without melting or softening.

That makes them useful for hot-structure components, thermal protection systems, and shielded enclosures on spacecraft and launch vehicles.⁶

The fiber-reinforced architecture of CMCs also reduces the brittleness typical of ceramics. This leads to damage absorption through controlled fiber pull-out and microcracking rather than catastrophic fracture.

As a result, CMCs are used in components like pressure vessels, nozzle liners, and reusable thermal protection tiles designed for repeated atmospheric entries and radiation exposure.

Experimental work has also indicated CMCs can be tailored to resist atomic oxygen erosion, extending component lifetimes in low Earth orbit.⁶

Radiation-resistant Metal Alloys and Structural Metals

Metal alloys still carry a lot of the load in space: primary structures, pressure hulls, and heat exchanger components depend on them. But conventional aluminum and stainless-steel alloys can harden, swell, or lose stability under radiation. To reduce that risk, researchers are developing radiation-resistant aluminum alloys with ultrafine-grained microstructures and stable hardening phases designed to tolerate proton and heavy-ion irradiation.

A recent study in [Advanced Materials](#) describes an ultrafine-grained alloy featuring a T-phase precipitate that helps stabilize the microstructure and limits damage at radiation levels that would typically degrade conventional alloys.⁷

These advanced alloys are engineered for high strength-to-weight ratios, corrosion resistance, and manufacturability, which makes them ideal for spacecraft hulls, cryogenic tanks, and secondary radiation shields. In parallel, radiation-resistant stainless steel and nickel alloys are being explored for high-temperature engine parts and protective vaults.

The broader goal is to predictably manage mechanical degradation over a mission's lifespan, allowing engineers to work within known radiation limits rather than rely on overly heavy shielding.^{7,8}

Carbon-based and Nanostructured Hybrid Systems

Carbon-based materials, like carbon fiber-reinforced polymers (CFRPs), carbon-carbon composites, and carbon nanotube-reinforced resins, have high specific strength and moderate radiation resistance. They're already commonly used in satellite structures, instrument benches, and booms, but long-term irradiation can still cause problems such as electrostatic discharge and dimensional instability.

One approach proposes embedding a superlattice nanobarrier of diamond-like carbon within the composite to absorb energetic protons and electrons while preserving the bulk mechanical properties of the CFRP.^{2,5}

Hybrid strategies are gaining attention elsewhere: adding nanostructured fillers like boron or lithium nanoparticles and metal-oxide clusters to polymers can result in combined radiation shielding, electrostatic conductivity, and atomic oxygen resistance. These materials can be applied as thin films or 3D-printed components, enabling tailored protection for specific radiation levels and mission durations.⁹

Testing, Simulation, and Long-duration Performance

When taking materials to space, standards are hypervigilant. Radiation-resistant materials are validated using standardized protocols to simulate space radiation. European and international standards, such as [ECSS-Q-ST-70-06C](#), lay out procedures for exposing non-metallic materials to electron, proton, and UV radiation, followed by property measurements.

Because real missions last years, these protocols usually involve accelerated exposures to simulate approximate long-term mission conditions within laboratory timeframes.¹⁰

Ground-based simulators add realism to tests with mixed radiation fields. NASA's Galactic Cosmic Ray simulator and heavy-ion facilities in Europe allow researchers to test sequences of protons and heavier ions at varied energies, approximating the complex radiation environment inside spacecraft.

Monte Carlo simulations, often using Geant4, complement experimental data by predicting dose distributions and shielding effectiveness for materials such as aluminum, polyethylene, and carbon-fiber-reinforced polymers.^{2,11}

Long-duration space missions face challenges from cumulative radiation damage, thermal cycling, and atomic oxygen exposure, which are hard to test in the short term.

To ensure durability, materials must be designed with built-in margins, such as stable microstructures, low-outgassing formulations, and multifunctional shielding layers that maintain performance over ten-year or longer missions.

As deep-space missions and orbital platforms increase, radiation-resistant materials must continue to evolve to balance protection, weight, and manufacturability across diverse space environments.^{2,3}

References and Further Reading

1. Li, H. et al. (2024). Research on B4C/PEEK Composite Material Radiation Shielding. *Polymers*, 16(20). DOI:10.3390/polym16202902. <https://www.mdpi.com/2073-4360/16/20/2902>
2. Naito, M., & Kodaira, S. (2022). Considerations for practical dose equivalent assessment of space radiation and exposure risk reduction in deep space. *Scientific Reports*, 12(1), 13617. DOI:10.1038/s41598-022-17079-1. <https://www.nature.com/articles/s41598-022-17079-1>
3. Toto, E. et al. (2024). Recent Advances and Challenges in Polymer-Based Materials for Space Radiation Shielding. *Polymers*, 16(3). DOI:10.3390/polym16030382. <https://www.mdpi.com/2073-4360/16/3/382>

4. Cha, J. *et al.* (2022). Functionalized multi-walled carbon nanotubes/hydrogen-rich benzoxazine nanocomposites for cosmic radiation shielding with enhanced mechanical properties and space environment resistance. *Composites Science and Technology*, 228, 109634. DOI:10.1016/j.compscitech.2022.109634.
<https://www.sciencedirect.com/science/article/abs/pii/S0266353822003761>
5. Delkowski, M. *et al.* (2023). Radiation and electrostatic resistance for ultra-stable polymer composites reinforced with carbon fibers. *Science Advances*. DOI:10.1126/sciadv.add6947. <https://www.science.org/doi/10.1126/sciadv.add6947>
6. Dhanasekar, S. *et al.* (2022). A Comprehensive Study of Ceramic Matrix Composites for Space Applications. *Advances in Materials Science and Engineering*, 2022(1), 6160591. DOI:10.1155/2022/6160591. <https://onlinelibrary.wiley.com/doi/10.1155/2022/6160591>
7. Willenshofer, P. D. *et al.* (2025). Radiation-Resistant Aluminum Alloy for Space Missions in the Extreme Environment of the Solar System. *Advanced Materials*, e13450. DOI:10.1002/adma.202513450.
<https://advanced.onlinelibrary.wiley.com/doi/10.1002/adma.202513450>
8. Kalita, P. *et al.* (2025). Progress in radiation tolerant materials: Current insights from the perspective of grain size and environmental temperature. *Journal of Alloys and Compounds*, 1012, 178330. DOI:10.1016/j.jallcom.2024.178330.
<https://www.sciencedirect.com/science/article/abs/pii/S0925838824049181>
9. Churchill, R. J. *et al.* (2013). NanoStructured Additives to High-Performance Polymers for Use in Radiation Shielding, Protection Against Atomic Oxygen and in Structural Applications. US20130161564A1. *Google Patents*.
<https://patents.google.com/patent/US20130161564A1/en>
10. ECSS-Q-ST-70-06C – Particle and UV radiation testing for space materials. ECSS.
<https://ecss.nl/standard/ecss-q-st-70-06c-particle-and-uv-radiation-testing-for-space-materials/>
11. Simonsen, L. C. *et al.* (2020). NASA's first ground-based Galactic Cosmic Ray Simulator: Enabling a new era in space radiobiology research. *PLoS Biology*, 18(5), e3000669. DOI:10.1371/journal.pbio.3000669. <https://journals.plos.org/plosbiology/article?id=10.1371/journal.pbio.3000669>

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New Concrete Method Resists Heat, Chemicals, and Cracking With Nano-Alumina

High shear-dispersed nano-alumina enhances concrete performance, unlocking stronger, denser, and more durable material for high-stress infrastructure.



Study: [Effect of high shear-dispersed nano-alumina on concrete strength, durability, and microstructure](#). Image Credit: Nature Peaceful/Shutterstock.com

A new study in *Scientific Reports* reveals that incorporating nano-alumina into concrete, using high-shear mixing, significantly boosts its strength, durability, and structural integrity. The researchers examined the role of nanoparticle dispersion in improving concrete performance, providing insights that could reshape how modern infrastructure is built and maintained.

The Role of Nanotechnology in Modern Concrete

Nanotechnology is steadily reshaping construction materials, particularly concrete, by enhancing performance characteristics such as strength and resistance to environmental stress.

Nano-alumina, with its high surface area and chemical reactivity, shows promise in addressing concrete's traditional weaknesses, namely, brittleness and reduced durability under extreme

conditions.

When properly dispersed, nano-alumina particles refine the pore structure, fill microvoids, and promote hydration, which results in a denser, more cohesive matrix. This enhances the bond between cement particles, improving both mechanical properties and resistance to wear.

However, the effectiveness of these enhancements depends heavily on achieving uniform nanoparticle dispersion, clumping (or agglomeration) can limit benefits.

Experimental Design and Methodology

The study tested nano-alumina additions at 0.5 %, 1.0 %, and 1.5 % by cement weight. High-shear mixing at 3000 rpm for 10 minutes was used to disperse the nanoparticles (10 – 30 nm) throughout the mixture.

Concrete specimens were tested after curing for 7, 28, 90, and 180 days, measuring:

- Compressive, split tensile, and flexural strength
- Durability under chemical attack (NaCl, HCl, H₂SO₄), freeze-thaw cycles, high temperatures (200°C, 400°C, 600°C), and water permeability

Microstructural changes were analyzed using scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDX). Researchers also used multivariable regression and Weibull analysis to assess strength reliability and forecast long-term performance.

Key Findings of Nano-Alumina Integration

The integration of nano-alumina led to significant improvements:

- Strength Gains (at 28 days, 1.5 % dosage):
 - Compressive: up 26.99 %
 - Split tensile: up 37.5 %
 - Flexural: up 48.14 %
- Extended strength at 180 days reached 74.04 MPa.

Durability also improved:

- Stronger resistance to chemical exposure, freeze-thaw cycles, and temperatures up to

400°C.

- At 600°C, all mixes showed performance drops, but nano-alumina-modified concrete still outperformed the control group.

Microstructural insights:

- Nearly 65 % reduction in average void size
- Formation of secondary C-A-S-H gel, contributing to denser internal structure
- Moderate RCPT readings explained by the ionic nature of pore fluids, not necessarily by poor permeability

Statistical analysis confirmed that higher nano-alumina dosages enhance reliability and consistency in strength performance.

Practical Applications for Construction Practices

These findings point to tangible benefits for infrastructure projects, especially in challenging environments exposed to mechanical, chemical, or thermal stress. Applications include bridges and overpasses, marine structures, and wastewater treatment facilities.

The use of high-shear mixing is particularly relevant as it offers a field-scalable, cost-effective alternative to more intensive lab-based methods like ultrasonication, improving real-world feasibility.

In terms of sustainability, while the study didn't quantify reductions in cement use or carbon footprint, the extended service life and reduced maintenance needs could indirectly support long-term environmental goals.

Conclusion and Future Directions

This research highlights how dispersion quality, not just nanoparticle dosage, is key to unlocking the full benefits of nano-alumina in concrete.

When properly mixed, nano-alumina can significantly enhance strength, durability, and reliability, supporting the development of high-performance concrete systems suited for modern infrastructure needs.

Future work should:

- Refine incorporation and mixing techniques
- Explore hybrid nanoparticle systems
- Evaluate field performance under real-world conditions
- Assess cost-effectiveness and sustainability impact

The integration of nanotechnology into cement systems presents a promising path toward smarter, longer-lasting, and more resilient construction materials.

Journal References

Rahman, I., & et al. (2026). Effect of high shear-dispersed nano-alumina on concrete strength, durability, and microstructure. *Sci Rep*. DOI: 10.1038/s41598-026-36760-3, <https://www.nature.com/articles/s41598-026-36760-3>

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Advanced Ceramics in the Lab: Reproducible Size Reduction and Clean Material Transfer

Technical ceramics, also known as advanced ceramics, have become essential materials for modern industrial and scientific applications. Their remarkable mechanical strength, chemical resistance, thermal stability, and electrical qualities enable them to outperform traditional materials in harsh environments.

Due to these properties, technical ceramics are widely used in several industries, including energy technology, aerospace, electronics, automotive engineering, medical devices, and advanced materials research.

The exceptional performance of technical ceramics, however, is inseparably connected to the challenges associated with their processing. Their brittleness, hardness, and abrasion tolerance make it difficult to perform size reduction, homogenization, and sample preparation.

Controlled, efficient, and contamination-free comminution procedures are, therefore, crucial for producing reliable analytical results and reproducible manufacturing processes for materials including aluminum oxide (Al_2O_3), zirconium oxide (ZrO_2), silicon carbide (SiC), and silicon nitride (Si_3N_4).

Offering a thorough introduction of technical ceramics from a processing standpoint, this article:

1. Describes why pre-crushing and grinding are necessary
2. Identifies appropriate milling procedures for challenging ceramic materials
3. Explores how current system solutions, like combination units and cyclone-assisted material handling, can enhance efficiency, cleanliness, and reproducibility

While the emphasis remains on ceramic materials and their preparation, cyclone technology is also explored as a complementary component that improves overall processing performance.

Implications for Processing

The same qualities that make technical ceramics appealing also make them challenging to process. High hardness causes increased wear on grinding equipment, and brittleness

necessitates careful size reduction to avoid excessive fines or unpredictable particle morphologies.

As a result, ceramic processing requires specialized equipment and well-planned workflows. Size reduction is an essential step in both analytical sample preparation and industrial ceramic manufacturing.

Whether the objective is quality control, material characterization, or additional processing, consistent particle size distributions and homogeneous samples are required.

Why Pre-Crushing Is Essential

Ceramic raw materials are commonly delivered in large, uneven bits. Directly fine grinding such materials is inefficient and may overwhelm milling devices, so pre-crushing has several important applications:

- **Reduction of feed size** protects fine-grinding tools
- **Improved process control** in subsequent milling steps
- **More uniform particle size distribution**
- **Shorter overall grinding times** and lower energy consumption

Jaw crushers are ideal equipment for this step, as they can handle huge feed sizes and extremely hard materials. To reduce contamination and wear, they can be equipped with abrasion-resistant jaws made of tungsten carbide, zirconium oxide, or toughened alloy.



Fig. 1. RETSCH's range of Jaw Crushers. Image Credit: RETSCH

Adjustable gap settings allow the output particle size to be matched to the needs of the

following processing step.

RETSCH jaw crushers offer a variety of solutions for pre-crushing technical ceramics, ranging from compact benchtop devices for small sample volumes to high-performance machines for industrial use.

Depending on the model, variables such as throughput, maximum feed size, contamination control, and ease of operation are prioritized. The table below clearly compares the important features of the aforementioned devices.

Source: RETSCH

Model	Design	Max. Feed Size	Gap Width	Throughput	Key Features	Typical Application
BB 50	Benchtop	up to 50 mm	0–11 mm Digitally adjustable in increments of 0.1 mm	Three liters per batch	Compact, digital gap display, easy to clean, various grinding tool materials (e.g., zirconium oxide)	Small sample batches, contamination-sensitive oxide ceramics
BB 200	Floor model	up to 90 mm	0–30 mm (continuous)	≤ 300 kg/h	Versatile, suitable for routine use	Pre-crushing of medium ceramic quantities
BB 300	Floor model	up to 130 mm	1–40 mm (continuous)	≤ 600 kg/h	Higher throughput, robust	Larger and tougher ceramic pieces
BB 250	Floor model	Up to 120 x ≤ 90 mm	0–30 mm (continuous)	≤ 300 kg/h	Front-door design, quick access, easy cleaning	Fast material changes, reduced cross-contamination
BB 400	Floor model	≤ 220 x 90 mm	0 – 30 mm (continuous)	≤ 400 kg/h	Front-door design, quick access, easy cleaning	Fast material changes, reduced cross-contamination
BB 500	Floor model	≤ 110 mm	0–11 mm (continuous)	≤ 500 kg/h	High crushing ratio (e.g., 90 % < 0.5 mm), protected hopper	Fast and reproducible size reduction
BB 600	Large-scale unit	≤ 350 x 170 mm	6–60 mm (with spacer plates)	≤ 3500 kg/h	Suitable for process lines, overload protection, low installation height	Industrial applications, large sample volumes

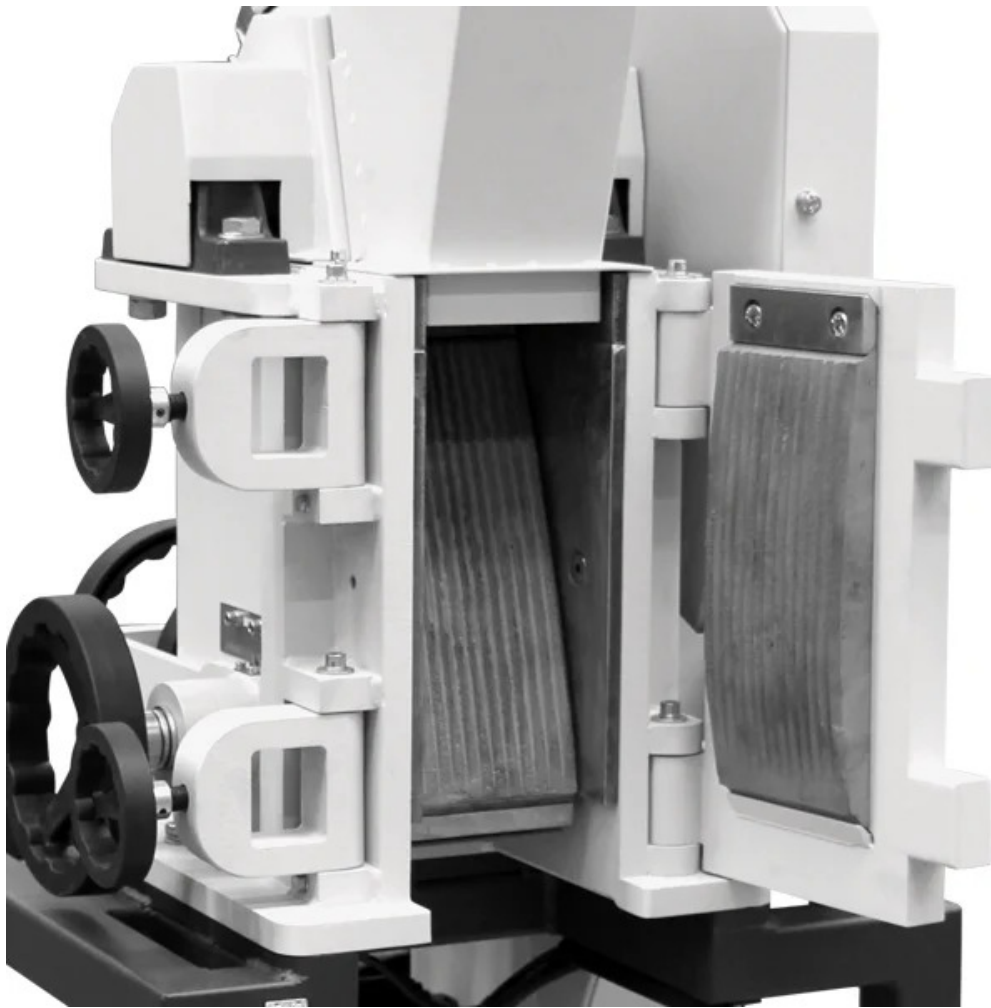


Fig. 2. The front door of the BB 250 allows for easy cleaning. Image Credit: RETSCH

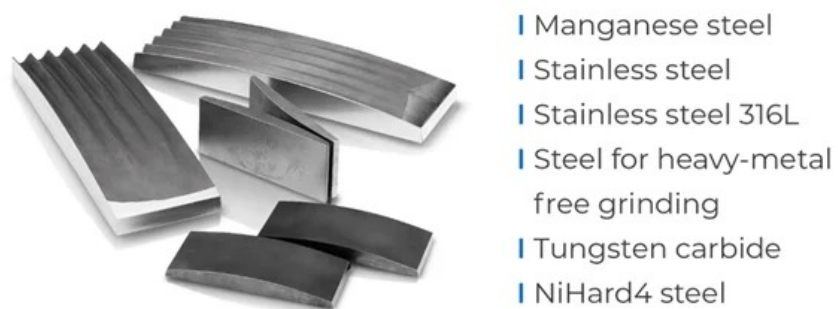
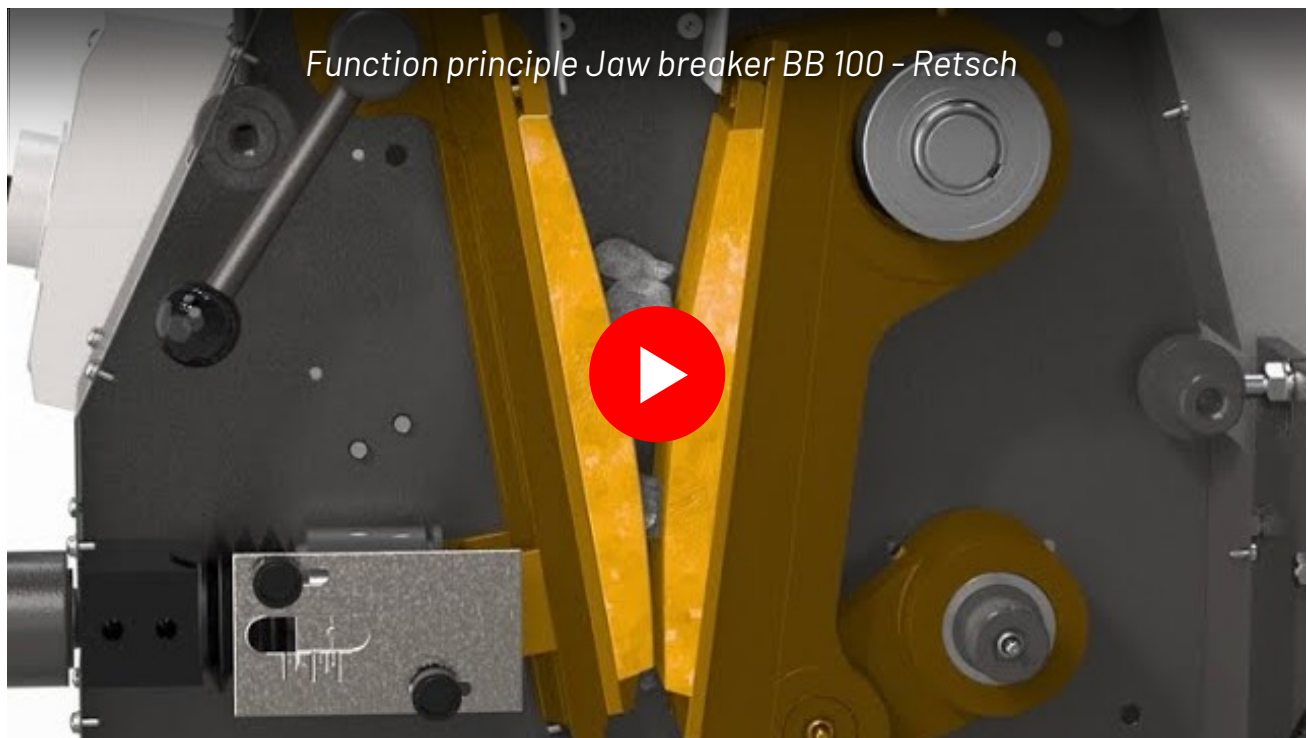


Fig. 3. Breaking jaws and wearing plates are available in different materials. Image Credit: RETSCH



Video Credit: RETSCH



Video Credit: RETSCH

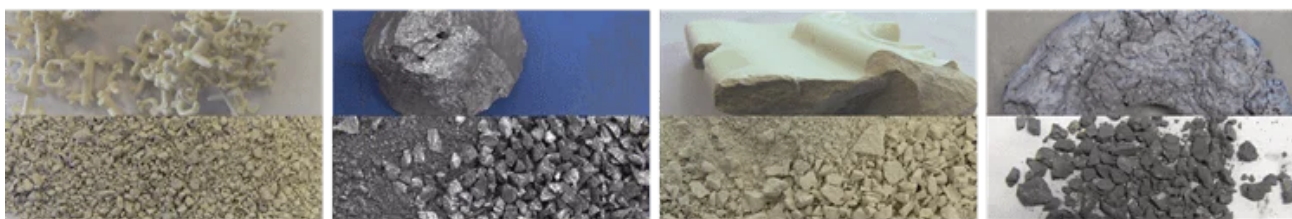


Fig. 4. Pictures of samples ground with jaw crushers (before and after grinding) from left to right: ceramics, silicon, calcium silicate, sinter cake. Image Credit: RETSCH

Fine Grinding and Homogenization

After the pre-crushing step, fine grinding is performed to get the desired final particle size. Depending on the application, this can range from several hundred micrometers to submicron or even nanometer scale.

Disc mills and planetary ball mills are frequently employed, depending on sample number, desired fineness, and tolerable wear. Homogenization ensures that analytical samples are representative and that ceramic powders behave consistently in subsequent procedures like sintering or shaping.

RETSCH disc mills are effective in producing narrow particle size distributions in the submillimeter range. Their robust design makes them appropriate for use with brittle, hard ceramics.

The RETSCH Disc Mill DM 200 is designed for the preliminary and fine grinding of medium-hard to hard, brittle materials. It reaches the desired grind size in a matter of minutes, which is useful when ceramic laboratories have a large number of samples to process each day.

Accurate, continuously adjustable gap settings as small as 0.05 mm help to ensure reproducibility. This enables finer tweaking while keeping consistent quality control conditions for ceramic raw materials.

A hinged grinding chamber facilitates cleaning and allows for quick material changes, reducing cross-contamination when moving between oxide and non-oxide ceramic compositions.

The DM 200 provides grinding discs in zirconium oxide or tungsten carbide for purity-critical

technical ceramics, which avoid or decrease metallic abrasion when compared to conventional steels. The dust extraction connector enables more efficient handling of fine ceramic powders.



Fig. 5. RETSCH Disc Mill DM 200. Image Credit: RETSCH

For even finer grinding, particularly when nanoscale particles are required, wet ball milling is frequently favored since the liquid phase aids in heat dissipation and deagglomeration of tiny ceramic particles.

In technical ceramics, ball milling is often used to create reactive, sinterable powders of Al_7O_8 , ZrO_8 , SiC , or Si_8N_8 with regulated particle size distributions that influence packing density and ultimate microstructure.

RETSCH planetary ball mills offer high energy input through combined impact and friction, allowing ultrafine grinding down to submicrons and, for colloidal applications, to below $0.1\text{ }\mu\text{m}$. The table below clearly compares the essential features of the Retsch Planetary Ball Mills.

Source: RETSCH

Product	Grinding stations	Max. jar volume	Max. speed / energy input	Advantages
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PM 100	1	500 mL	650 rpm; energy input up to 33.3 g	Ideal for single-batch work; flexible jar sizes; wide selection of jar materials for contamination-free dry or wet grinding; high reproducibility through speed control
PM 200	2	125 mL	650 rpm; energy input up to 37.1 g	Parallel processing of ceramic formulations (e.g., doped vs. undoped); short grinding times at high energy input
PM 300	2	500 mL	800 rpm; energy input up to 64 g	Highest energy input of all RETSCH planetary ball mills; reduced grinding times and finer particles, especially for hard materials in wet grinding
PM 400	4	500 mL	400 rpm; energy input up to 26.8 g	High sample throughput; simultaneous processing of multiple jars; suitable for design-of-experiments studies on dispersants, binders, or sintering aids

When maximum energy input and short process times are required, the High Energy Ball Mill Emax combines high friction and impact at high speed. It generates energy forces of up to 76 g and uses water cooling to allow temperature-controlled grinding, which protects temperature-sensitive ceramic suspensions and decreases the need for cooling breaks.

Its unique jar design facilitates mixing and can produce narrow particle size distributions, resulting in more consistent ceramic green-body behavior.

In addition to planetary systems, RETSCH **mixer mills**, such as the MM 500 nano, offer a compact, high-energy solution for technical ceramics when small batch volumes and rapid comminution are required.

The MM 500 nano can operate at up to 35 Hz and generate enough energy for wet nano-grinding (claimed final fineness of approximately 0.1 μm , depending on the material).

The horizontal oscillation approach often generates less heat than traditional high-energy methods, resulting in stable dispersion conditions for ceramic slurries. The MM 500 nano and MM 500 control, which have two grinding stations and pressure-tight Screw-Lock jars (up to 125 ml), allow for concurrent processing of ceramic formulations.

They also improve repeatability by allowing jars to be clamped during subsampling and by storing SOPs (Standard Operating Procedures) and programmed cycles. The MM 500 control is especially useful for temperature-sensitive technical ceramics containing organic binders, dispersants, or hydration processes.

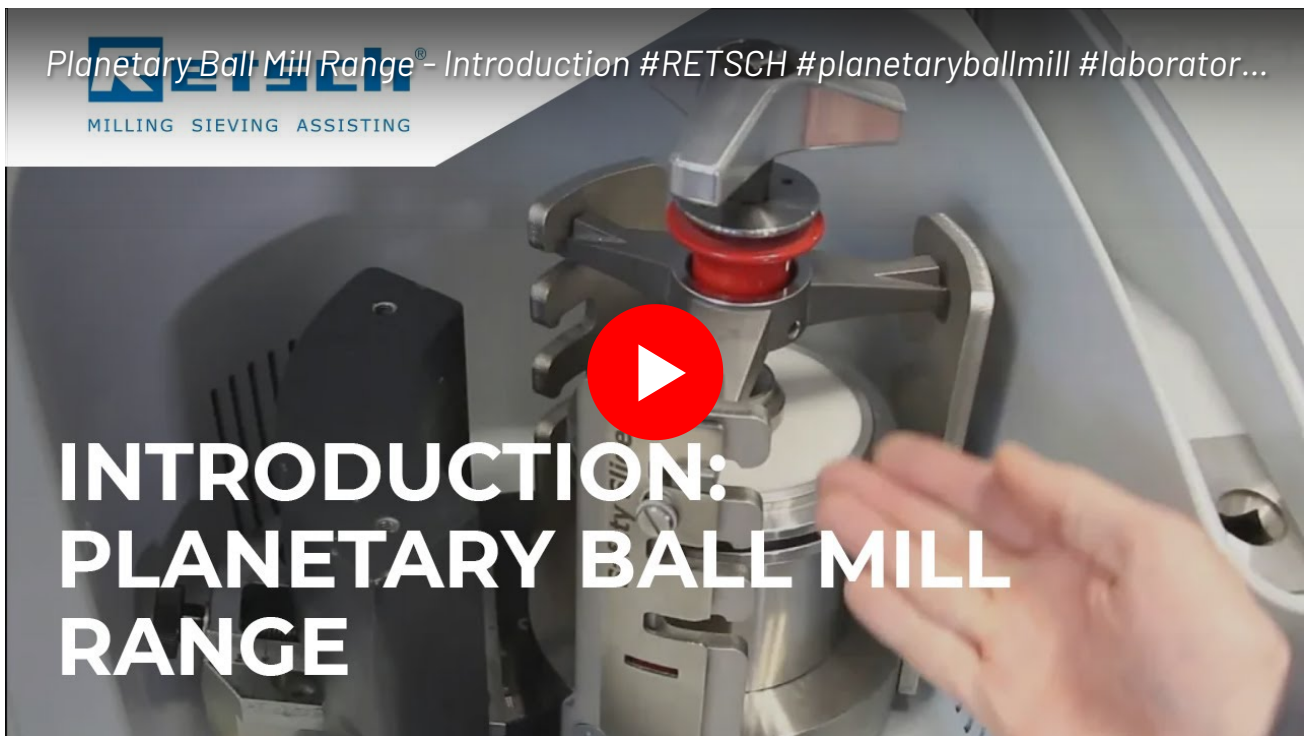
It facilitates the monitoring and controlling of the grinding temperature over approximately -100 to +100 °C. This temperature control aids in maintaining constant rheology and reducing unexpected reactions during high-energy milling of advanced ceramic powders.

Among these ball-milling choices, selecting jars and balls composed of zirconium oxide is crucial for limiting contamination, particularly for electrical or optical ceramics where trace metals can impair characteristics.

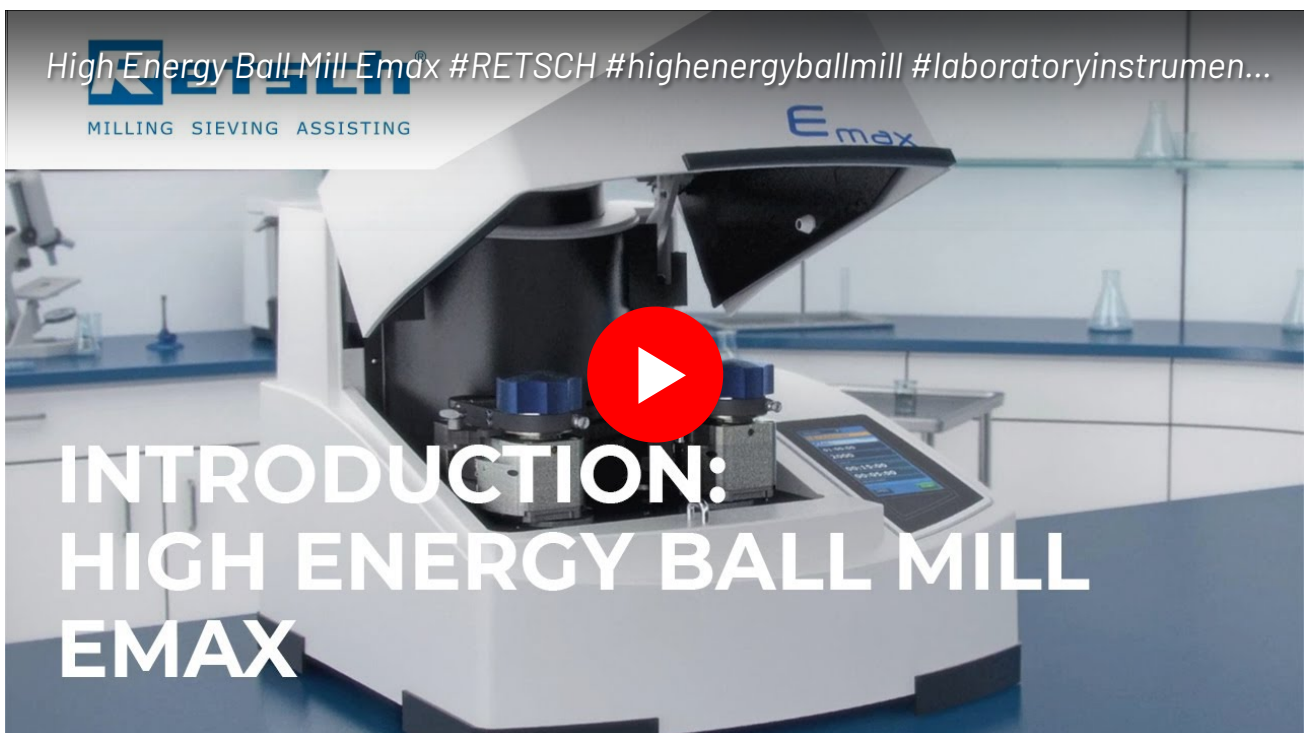
Process parameters such as speed, duration, direction reversal, and solid loading should be chosen to balance fineness and wear. They should also be regulated to prevent excessive amorphization and unwanted mechanochemical reactions in sensitive ceramic systems.



Fig. 6. RETSCH's range of Ball Mills. Image Credit: RETSCH



Video Credit: RETSCH



Video Credit: RETSCH



Video Credit: RETSCH

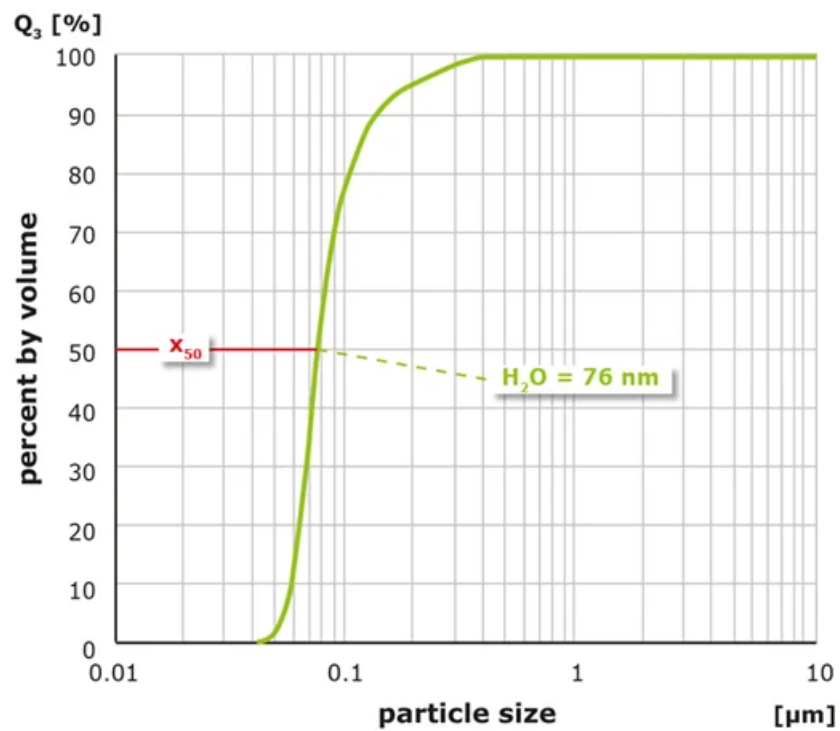


Fig. 7. Grinding of alumina in PM 100 with one millimeter grinding balls (one hour) and then with 0.1 mm balls (three hours) in water. Image Credit: RETSCH

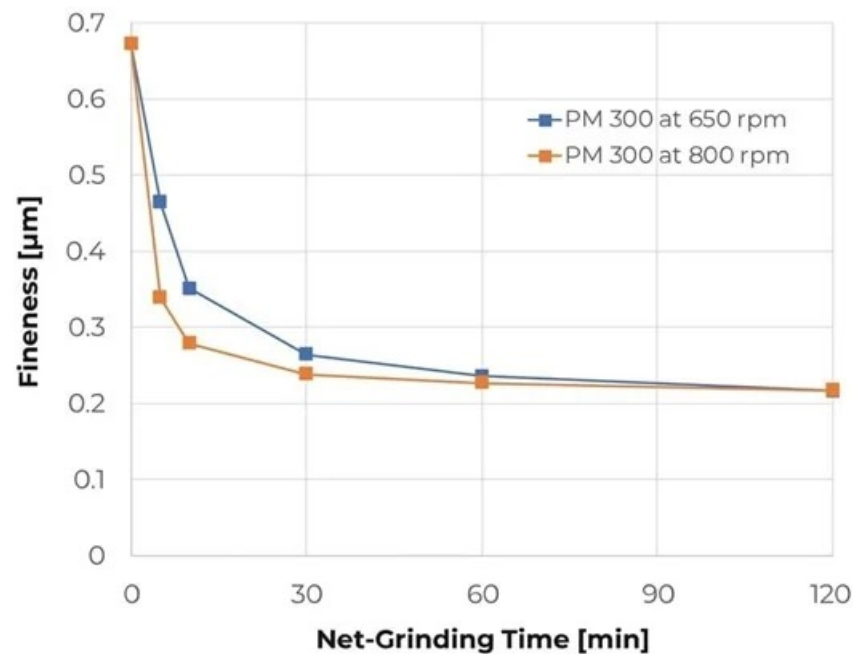


Fig. 8. Net processing time of titanium dioxide in PM 300 with 0.1 mm grinding balls in sodium phosphate solution. Image Credit: RETSCH

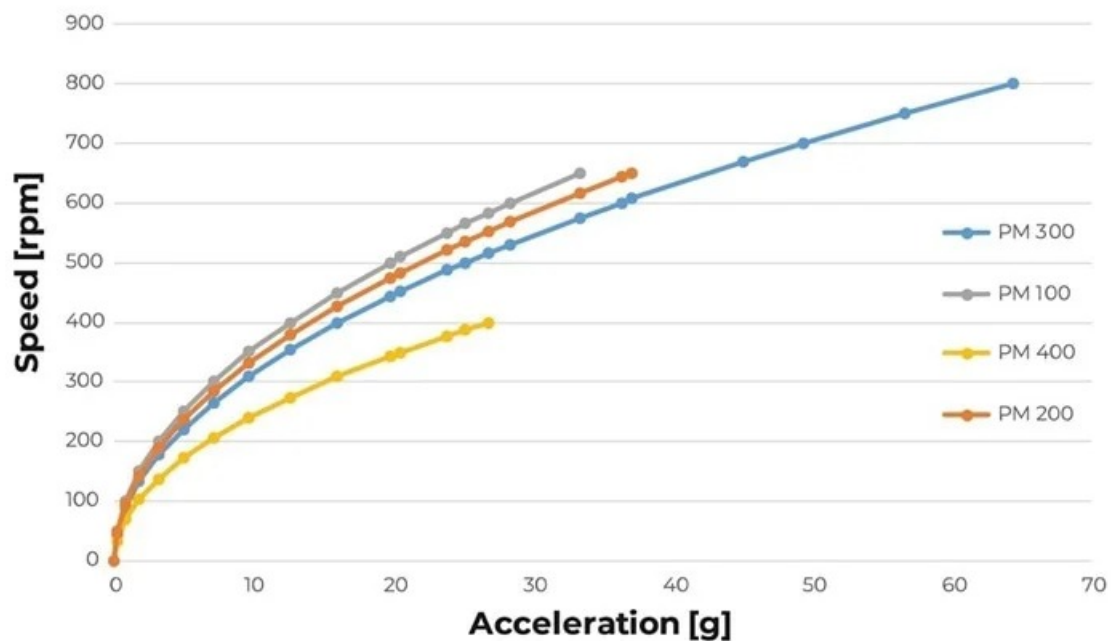


Fig. 9. Achievable acceleration in different planetary ball mills dependent on speed setting. Image Credit: RETSCH

Integrated Processing: Combination Units for Efficiency

Conventionally, ceramic processing has used multiple separate devices: a jaw crusher for pre-

crushing, followed by sample transfer, optional splitting, and fine grinding in a second machine. Though this method is adaptable, it is time-consuming and susceptible to sample loss or contamination.

Modern combination units integrate two size reduction processes, usually a jaw crusher and a disc mill, into a single, continuous workflow, together with a cyclone separator.

Material is delivered straight from the pre-crushing stage to the fine grinding stage and collected in a vessel following the cyclone unit, eliminating the need for manual handling. For technical ceramics, combination units offer various advantages:

- **Reduced handling time** and fewer process steps
- **Less risk of sample loss or segregation**
- **Improved reproducibility**, especially for analytical samples
- **Dust reduction**, creating a safer environment
- **Samples require less heating**, thanks to the generated air stream
- **Protection of machine components**, such as bearings, from abrasive dust

These methods are especially suitable for processing medium-sized sample amounts that do not require intermediate splitting. While size reduction is the primary goal of ceramic processing, sample recovery, dust control, and heat management are critical in actual laboratory and process contexts.

Often, fine ceramic particles stick to grinding chambers, tools, and connecting parts, and high-energy grinding can cause temperature increases, which may alter material characteristics or analytical results. Cyclone systems are used to aid grinding processes by removing the particles generated during milling from the airflow.

In the context of technical ceramics, cyclones should be viewed as process enhancers rather than grinding instruments. They improve cleanliness, reproducibility, and operator safety, particularly in integrated or high-throughput settings.

Most RETSCH Jaw Crushers and the Disc Mill DM 200 can be supplied with cyclones as standalone devices, without the need for pre-crushing and fine grinding.

Small analytical samples and large industrial batches demand distinct approaches. While

combination units and cyclone-assisted systems perform well in medium-throughput applications, very large amounts may benefit from staged processing with interim sample division.



Fig. 10. RETSCH Hammer Mill HM 200 with attached Cyclone System. Image Credit: RETSCH



Fig. 11. Combination unit of two Mills – Jaw Crusher BB 250 with Disc Mill DM 200 and attached Cyclone System. Image Credit: RETSCH

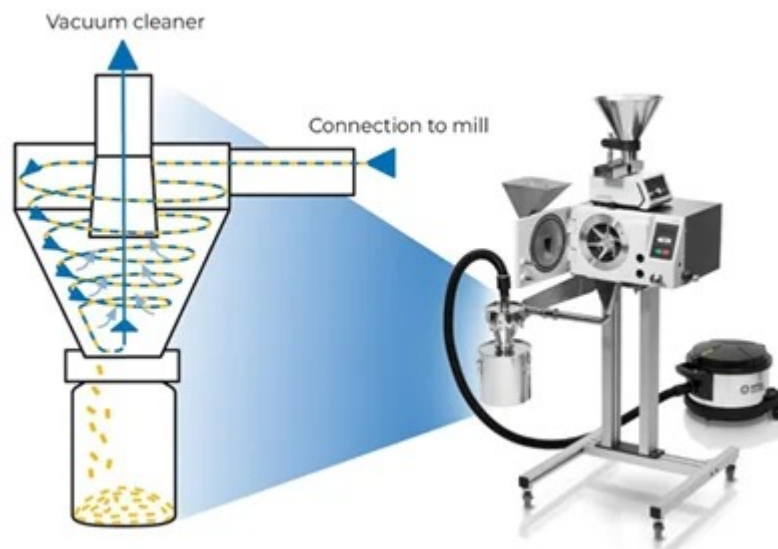


Fig. 12. RETSCH Rotor Beater Mill SR 300 mill with a cyclone setup and schematic representation of the functional principle. Image Credit: RETSCH

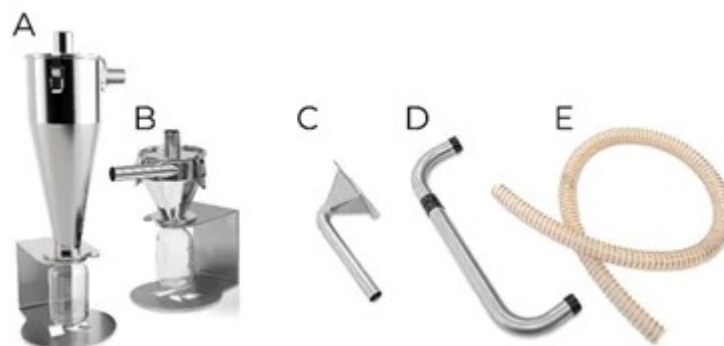


Fig. 13. RETSCH cyclone variants: high-efficiency version (A) and the standard version (B), as well as options for mounting such as rigid piping (C), flexibly adjustable connections (D), and FDA-compliant hoses (E) for installation on the sample outlet of the mill. Image Credit: RETSCH

Conclusion

Technical ceramics are among the most difficult material groups in modern processing technologies. Their outstanding mechanical and thermal qualities allow for high-performance applications, but achieving their full potential requires carefully designed size reduction tactics.

Efficient processing starts with regulated pre-crushing, which is followed by fine grinding according to the required particle size and application. Jaw crushers, disc mills, and ball mills form the foundation of ceramic comminution, while integrated combination units considerably increase workflow efficiency and reproducibility.

Supporting technologies - such as cyclone-assisted material handling - improve process cleanliness, sample recovery, and heat control, particularly in laboratory settings.

Although these systems are not as crucial as the core grinding equipment, they do provide a significant contribution to safe, efficient, and reliable ceramic processing.

As technical ceramics become more important in various industries, efficient preparation and comminution procedures will continue to be critical success factors, bridging the gap between advanced material qualities and practical, real-world applications.



This information has been sourced, reviewed, and adapted from materials provided by RETSCH.

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What Makes Gallium Nitride Important for Power Electronics?

In power electronics, gallium nitride can help engineers build smaller, faster, and more efficient systems than silicon can support.

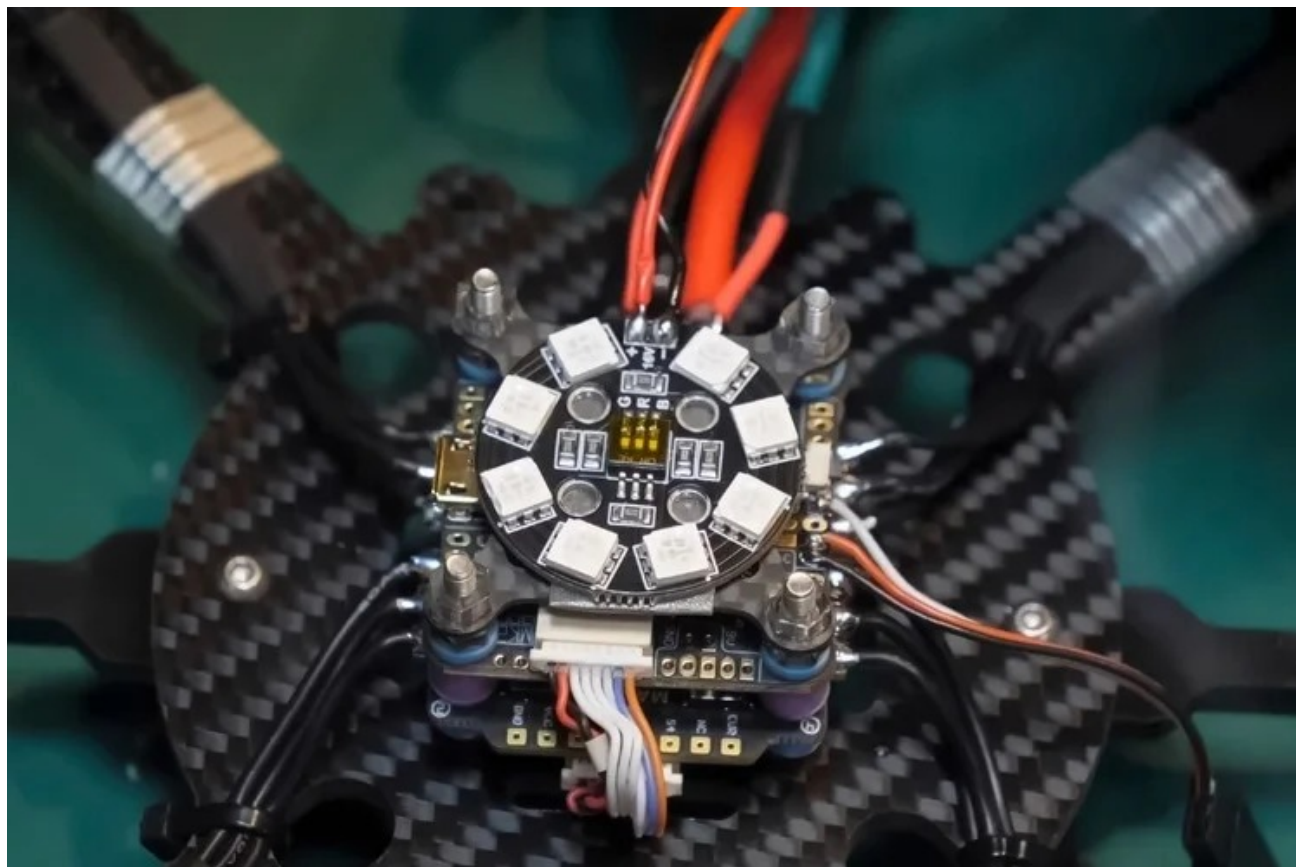


Image Credit: Olga_Kostrova/Shutterstock.com

As industries push toward decarbonization and face rising electricity demand from AI infrastructure, GaN is becoming an increasingly important material for next-generation power devices.

For decades, silicon (Si) has been the foundation of semiconductor technology. However, its physical limits are becoming more visible as designers pursue higher efficiency, greater power density, and faster switching speeds. That gap has increased interest in advanced materials that can support the next wave of progress in power conversion.

Among emerging candidates, Gallium Nitride (GaN) has established itself as a leading wide bandgap (WBG) semiconductor with the potential to reshape modern electronics. In power

electronics, GaN devices can switch faster, reduce energy loss, and shrink system size compared with silicon-based alternatives. That combination has made GaN increasingly relevant across automotive, industrial, data center, renewable energy, and consumer applications.¹

This article explains the material properties of GaN and how they translate into practical performance advantages in power electronics.

Fundamental Material Properties of GaN

The performance of GaN power devices starts with the material itself. Several core properties explain why gallium nitride is so attractive for power electronics.²

Wide Bandgap

GaN has an energy bandgap of about 3.4 eV, compared with 1.1 eV for silicon. This wider bandgap allows devices to operate at higher voltages, temperatures, and electric fields without breaking down as easily. It also contributes to lower intrinsic carrier concentration and leakage current, helping reduce energy loss during operation.³

High Electron Mobility

GaN-based high-electron-mobility transistors (HEMTs) use polarization effects to create a high-density two-dimensional electron gas (2DEG) at heterointerfaces. Electrons in this channel typically exhibit mobility in the 1500-2000 cm²/V s range, supporting fast charge transport and low on-resistance.

In practical terms, that means lower conduction losses and better high-frequency performance.

High Breakdown Electric Field

GaN has a critical breakdown field of roughly 3.3 MV/cm, compared with about 0.3 MV/cm for silicon. This large advantage allows GaN devices to block higher voltages across shorter distances. As a result, device layers can be thinner, lowering the specific on-state resistance. This is one of the main reasons GaN can maintain strong efficiency at higher voltage ratings where silicon begins to struggle.⁴

Thermal Stability

The wide bandgap also contributes to excellent thermal stability. GaN devices can operate at higher junction temperatures with minimal performance degradation, reducing cooling requirements and improving reliability in high-power environments.⁵

GaN vs Silicon vs Silicon Carbide

GaN can't replace every other semiconductor material. Instead, it fits into a broader power-electronics landscape alongside silicon and silicon carbide (SiC); each has distinct strengths.

Property	Silicon (Si)	Silicon Carbide (SiC)	Gallium Nitride (GaN)
Bandgap (eV)	1.12	3.2	3.4
Critical Field (MV/cm)	0.3	2.5-3.5	3.3
Electron Mobility (cm ² /Vs)	1450	700-1000	1500-2000
Thermal Conductivity (W/m·K)	150	300-490	130-210
Switching Frequency	Low (<100 kHz)	Medium (100 kHz)	High (1-10 MHz)

Silicon remains the most economical option for low-power, cost-sensitive applications. Silicon carbide is especially strong in high-voltage systems above 1200 V, including electric vehicle traction inverters. GaN is particularly effective in the 100 V to 700 V range, where high switching speed, compact size, and improved efficiency are major design priorities.

Key Application Domains

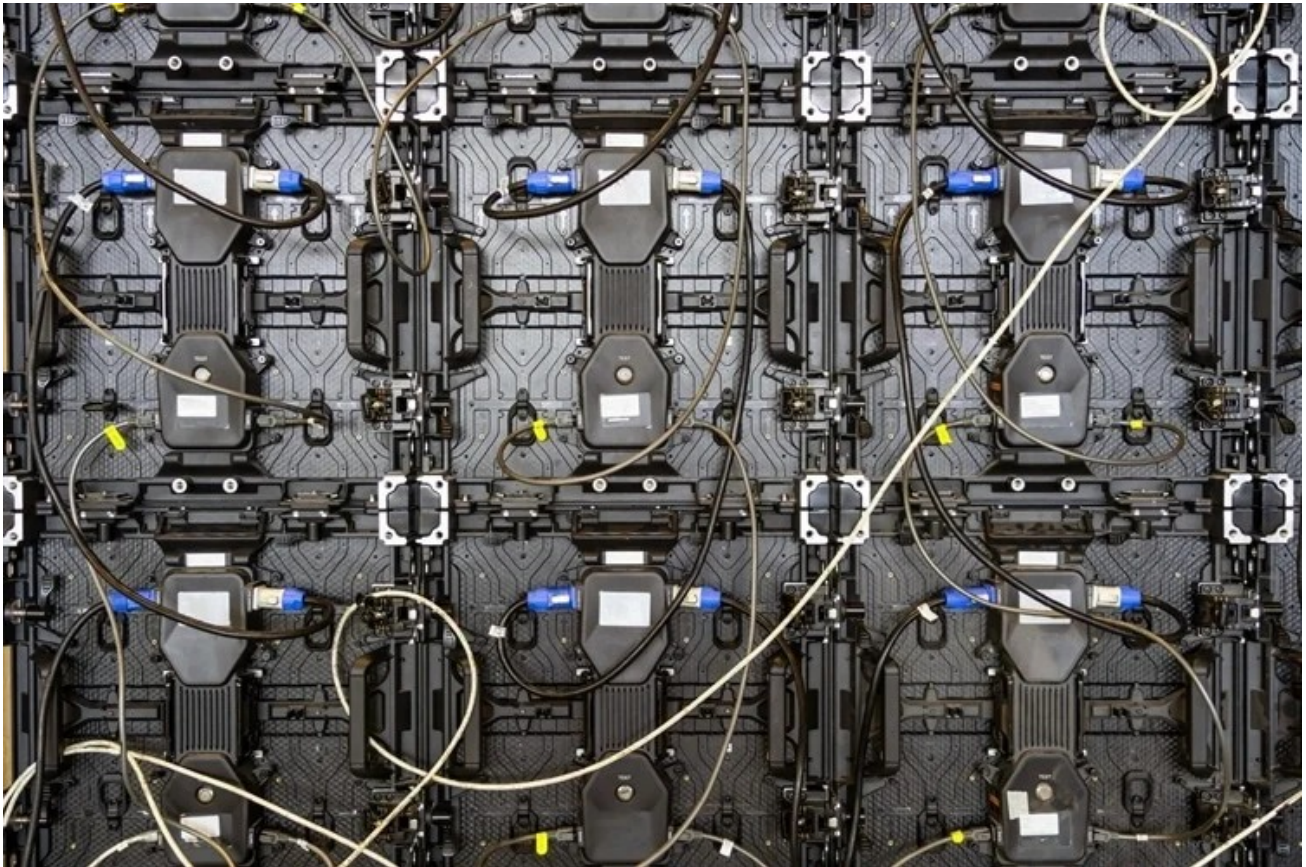


Image Credit: aapsky/Shutterstock.com

1. Electric Vehicles (EVs)

GaN is transforming EV power systems, particularly in on-board chargers (OBCs) and DC-DC converters. GaN-based OBCs can achieve efficiencies of 96-98 %, enabling a 30-60 % reduction in system volume.

Recent research in *IEEE Transactions on Electron Devices* (2026) highlights the development of p-GaN gate structures with threshold voltages exceeding 4 V, improving device safety and reliability for automotive applications.

2. Data Centers and AI Infrastructure

AI-driven data centers are highly energy-intensive, with projections indicating they may account for up to 12 % of U.S. electricity consumption by 2028.⁶ GaN-based power supplies can reduce energy losses by up to 30 %, enabling higher computational density while lowering cooling requirements.

New Resonant Tunneling Transistor (RTT) architectures based on GaN are now being proposed to merge power conversion with high-speed AI logic processing on a single chip.⁷

3. Renewable Energy and Consumer Electronics

In solar microinverters, GaN bidirectional switches enable single-stage power conversion, delivering up to 40 % higher power density with efficiencies exceeding 97.5 %. In consumer electronics, GaN has become the benchmark for fast-charging solutions, offering up to 3x faster charging in significantly smaller form factors than silicon-based adapters.⁸

Outlook and Conclusion

Gallium nitride is gaining attention in power electronics because it addresses several of silicon's core limitations. Its wide bandgap, strong breakdown field, high electron mobility, and thermal stability support faster switching, lower losses, and more compact system designs.

As manufacturing improves and integration matures, GaN is moving from specialized use cases into broader deployment across automotive, energy, data center, and consumer markets. For engineers working on efficient and scalable power systems, gallium nitride is becoming less of a niche option and more of a practical design choice.

References

1. Meneghini M, De Santi C, Abid I, Buffolo M, Cioni M, Khadar RA, et al. GaN-based power devices: Physics, reliability, and perspectives. *Journal of Applied Physics*. 2021;130(18).
2. Musumeci S, Barba V. Gallium nitride power devices in power electronics applications: State of art and perspectives. *Energies*. 2023;16(9):3894. **DOI:**10.3390/en16093894, <https://www.mdpi.com/1996-1073/16/9/3894>
3. Rais-Zadeh M, Gokhale VJ, Ansari A, Faucher M, Théron D, Cordier Y, et al. Gallium nitride as an electromechanical material. *Journal of Microelectromechanical Systems*. 2014;23(6):1252–71. **DOI:**10.1109/JMEMS.2014.2364251, <https://ieeexplore.ieee.org/document/6942177>
4. Chen C, Liu Y, Zhou X, Li P, Zhang Y, Yang B, et al. 4.11 A/1650 V Sapphire-Substrate GaN MIS-HEMTs with Thin Buffer for Medium-Voltage Power Applications. *Micromachines*. 2026;17(2):233. **DOI:**10.3390/mi17020233, <https://www.mdpi.com/2072-666X/17/2/233>
5. Avraham T, Dhyani M, Bernstein JB. Reliability Challenges, Models, and Physics of Silicon

Carbide and Gallium Nitride Power Devices. *Energies*. 2025;18(5):1046.

DOI:10.3390/en18051046, <https://www.mdpi.com/1996-1073/18/5/1046>

6. Clancy H. The data center boom threatens climate goals. How to fight back. 2025.
7. Liu F, Xue J, Wu G, Yuan J, Yao J, Liu R, et al. Gallium Nitride Semiconductor Resonant Tunneling Transistor. *Advanced Science*. 2026:e16334.
8. Renesas. Renesas Unveils First Bidirectional 650V-Class GaN Switch For Solar Power Inverters, AI Data Centers and More. 2026.

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Silicon Carbide Motor Drive Powers Successful Hybrid Test Flight

A hybrid plane has been flight-tested, equipped with a silicon carbide-based electric motor drive, rather than a traditional silicon system. This development could be used to make aviation lighter, more efficient, and more commercially available.



Study: [*Development, Integration, and Flight Testing of a Silicon Carbide Propulsion Drive for a Hybrid Electric Aerospace Application*](#). Image Credit: [adaptice photography/Shutterstock.com](#)

Alongside the electric engine and conventional gas-powered motor, an experimental silicon-carbide inverter was used in the motor of the hybrid Cessna 337 plane, which has been flight-tested in Southern California. This inverter was designed by the [University of Arkansas Power Group](#),

The test flight demonstrated that the conventional silicon-based motor drive system in a hybrid plane could be replaced with a more compact and effective silicon carbide-based system. The findings of this test flight, which took place in 2023, were published recently in the journal [*IEEE Transactions on Power Electronics*](#).

“ We were the first university to do this for a hybrid electric aircraft. That's a feather in our cap.

Alan Mantooth, Study Lead Researcher and Distinguished Professor, Electrical Engineering and Computer Science, University of Arkansas

The research received funding from the Department of Energy's Advanced Research Projects Agency-Energy, or ARPA-E.

The Advantages of Silicon Carbide

Transistors are the basis of electric circuits, functioning as amplifiers or switches. The microchips in computers and smartphones, for example, include billions of transistors that turn on and off to generate the binary language of ones and zeros. Today, most transistors are composed of silicon, which is formed by heating purified sand.

Transistors, however, cannot turn on and off instantly. Energy is wasted during the transition between the two states, although this occurs in only a fraction of a second. This lost energy generates heat.

Silicon carbide transistors can switch 1000 times quicker than those made of silicon. The quicker switching speed increases the transistor's efficiency, allowing all other components, such as inductors, transformers, and capacitors, to be significantly smaller and lighter.

“ Imagine a race car with a big 350 engine that weighs hundreds of pounds. What if you had that same power, but I gave you something that would fit in your hand?

Chris Farnell, Assistant Professor, Electrical Engineering and Computer Science, University of Arkansas

The University of Arkansas Power Group is a recognized leader in silicon carbide research and application. Despite its improved performance, the higher cost of silicon carbide has limited its widespread adoption.

“Silicon is made from dirt, and nothing is cheaper than dirt,” Mantooth added.

The cost of making silicon carbide, however, has been decreasing. Furthermore, the overall system cost is lower when using silicon carbide systems since they require fewer supporting components.

“ *If the overall system gets cheaper, then Ford cares, Toyota cares. That's why it ends up in cars.*

Alan Mantooth, Study Lead Researcher and Distinguished Professor, Electrical Engineering and Computer Science, University of Arkansas

Current silicon carbide production techniques, however, are not yet advanced enough to economically produce the nanometer-scale devices necessary for creating computer microchips. The UA Power Group is set to establish the Multi-User Silicon Carbide Research and Fabrication Laboratory to advance research on silicon-carbide microchip creation and connect university researchers with manufacturers.

The Challenges of Aviation

For the airplane trial, the UA Power Group developed a silicon carbide-based inverter that converts a battery's direct current into the alternating current needed to power a motor. A silicon carbide-based system's smaller size is especially useful aboard a smaller airplane with limited room.

“You're able to remove stuff and give passengers more legroom,” Farnell stated.

The reduced weight of a silicon-carbide system also means that the plane requires less energy to take off and cruise.

Electrical engineers have unique challenges while working on planes. To survive vibrations and landing stress, electrical systems must be mechanically supported.

At higher elevations, drier air increases partial discharge, which can weaken insulation and produce electrostatic problems. Additionally, other aviation systems may be affected by the increased electromagnetic interference resulting from silicon carbide's faster switching speed.

The Cessna 337's successful test flight demonstrated that the UA Power Group team was able

to deal with these challenges.



Video Credit: University of Arkansas

Journal Reference:

Farnell, C. et.al. (2025) Development, Integration, and Flight Testing of a Silicon Carbide Propulsion Drive for a Hybrid Electric Aerospace Application. *IEEE Transactions on Power Electronics*. doi.org/10.1109/TPEL.2025.3597905

Source:

[University of Arkansas](#)